Balancing Europe's wind power output through spatial deployment informed by weather regimes

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Summary paragraph (182 words)

As wind and solar power provide a growing share of Europe's electricity[1], understanding and accommodating their variability on multiple timescales remains a critical problem. On weekly timescales, variability is related to long-lasting weather conditions, called weather regimes[2–5], which can cause lulls with a loss of wind power across neighbouring countries[6]. Here we show that weather regimes provide a meteorological explanation for multi-day fluctuations in Europe's wind power and can help guide new deployment pathways which minimise this variability. Mean generation during different regimes currently ranges from 22 GW to 44 GW and is expected to triple by 2030 with current planning strategies. However, balancing future wind capacity across regions with contrasting inter-regime behaviour – specifically deploying in the Balkans instead of the North Sea – would almost eliminate these output variations, maintain mean generation, and increase fleet-wide minimum output. Solar photovoltaics could balance low-wind regimes locally, but only by expanding current capacity tenfold. New deployment strategies based on an understanding of continent-scale wind patterns and pan-European collaboration could enable a high share of wind energy whilst minimising the negative impacts of output variability.

Main Text (2059 words)

Climate change mitigation requires lowering the carbon intensity of energy systems[7]. Wind and solar photovoltaics (PV) are key technologies to achieve this objective. In Europe they are projected to jointly reach 420 GW and cover 25% of electricity generation by 2030[1]. Electricity generation is therefore becoming increasingly dependent on variable weather patterns. Intra-annual variations of generation range from hours and days to weeks and seasons. A wider geographic distribution of wind and PV can smooth power output variations[8,9] and increase fleet-wide minimum output, emphasizing the need for transmission in scenarios of 100% renewables[10–11]. Co-deployment of wind and solar PV can balance diurnal and seasonal variability locally[12-14]. However these strategies cannot address the problem of large variations in output that last several days or a few weeks. These variations affect neighbouring countries[6] and are difficult to balance with storage or flexible demand[15]. The frequency in time and correlation in space of such multi-day variations is currently not well understood[16].

The variability in weather on a spatial scale of about 1000 km and for time periods of more than five days can be categorized in "weather regimes"[3–5]. "Blocked regimes" exhibit high surface pressure, strongly reduced winds, and often fog and cold conditions during winter. "Cyclonic regimes" are characterized by strong winds, extratropical cyclones, and mild conditions. The North-Atlantic Oscillation (NAO)[2] provides a binary classification for the Atlantic-European region into a cyclonic (positive NAO) and a blocked (negative NAO) regime with implications for the energy sector on seasonal timescales[17,18]. More detailed classifications use four Atlantic-European weather regimes[3–5]. However, neither NAO nor these four regimes are sufficiently detailed to fully understand variability in surface weather on timescales of several days to weeks[19-21].

Therefore, we employ an extended classification of seven weather regimes designed to capture year-round, large-scale flow variability in the Atlantic-European region (Supplementary Discussion 1, Supplementary Figs. 1, 2). These weather regimes exhibit important differences in surface weather on multi-day timescales that are relevant for renewable electricity. Three regimes are cyclonic (Atlantic trough AT, zonal regime ZO, Scandinavian trough ScTr), and four blocked (Atlantic ridge AR, European blocking EuBL, Scandinavian blocking ScBL, Greenland blocking GL). In the following we demonstrate that the European energy system would strongly profit from exploiting the implications of these regimes for continent-scale wind generation patterns. The study focuses on winter (December, January, February – DJF) when the combined generation from Europe's wind and PV fleet is highest. However, our findings hold year-round (Supplementary Discussions 2-6, Supplementary Figs. 3-10).

As a measure of electricity generation we use national aggregate capacity factors (*CF*) simulated with the Renewables.ninja models[22,23]. *CF* is generation normalized by installed capacity and can be interpreted as the potential for generation in countries with equal installed capacities. For wind and PV, *CF* is highly dependent on meteorological conditions beyond technological and site-specific limitations.

Weather regimes affect wind power output, i.e. *CF*, on the continental scale (Fig. 1). Northern Europe, Southeastern Europe, and the Western Mediterranean are three sub-regions with different weather regime-dependent behaviour. Countries adjacent to the North and Baltic Seas have a high potential for overproduction (relative to the seasonal mean) of up to 50% during cyclonic regimes and risk underproduction of up to 50% during blocked regimes. In contrast, Southeastern Europe has the potential for overproduction during all blocked regimes, with up to 50% during EuBL, while underproduction of up to 40% prevails during the cyclonic AT and ZO regimes. In the Western Mediterranean wind generation does not correlate consistently with cyclonic and blocked regimes. Overproduction of up to 40% occurs during AT, ScBL, and GL, but underproduction of up to 30% occurs during ZO and EuBL. Also northern Scandinavia (e.g. Norway and Finland) exhibits overproduction during both cyclonic and blocked regimes. Europe as a whole has lower regime-dependent variability but still experiences changes of up to ±20% (inset Fig. 1).

These electricity generation patterns are caused by different wind conditions during the seven weather regimes (Fig. 2). The three cyclonic regimes (38.2% of all winter days, Fig. 2a-c) have an enhanced Icelandic low with a shift towards the south (AT), the east (ZO), or into Scandinavia (ScTr) compared to climatology (Fig. 2i). These modulations strongly enhance near-surface winds and increase temperature in vast parts of Europe (Figs. 2a-c, Supplementary Fig. 9). During the four blocked regimes (38.8% of winter days) stationary anticyclones disrupt the mean westerly flow into Europe, near-surface winds are strongly reduced, and cold conditions prevail (Figs. 2d-g, Supplementary Fig. 9). However, the stationary anticyclones are flanked by cyclonic activity, enhancing winds in peripheral regions. For example, during EuBL (Fig. 2e) weak winds extend over vast parts of Europe but Northern Scandinavia and the Balkans experience enhanced winds. Albeit causing a severe lull, EuBL is on average NAO positive.

We now consider wind *CF* in Europe and in representative countries (Fig. 3). In Europe, absolute wind *CF* is higher during cyclonic regimes (0.37 during AT and ScTr) and lower during blocked regimes (0.25 during EuBL). Germany, representative of the North Sea region, behaves similarly, but with lower mean and greater amplitude (Fig. 3b). In contrast, in Greece, representative of Southeastern Europe, *CF* is higher than the seasonal mean during blocked regimes and lower during cyclonic regimes (Fig. 3d). In Spain, representative of the Western Mediterranean, *CF* is highest during the cyclonic AT regime (0.42, Fig. 3c), but the blocked ScBL and GL regimes also exhibit increased *CFs*.

Mean generation for Europe shows stronger weather regime-dependent fluctuations than *CF* (Figs. 3a,e, Supplementary Table 3), because of the uneven distribution of capacity across the continent (Fig. 1, Supplementary Fig. 11). Overproduction occurs during cyclonic regimes peaking at 44.2 GW for AT. Underproduction occurs during blocked regimes, with 21.8 GW during EuBL. Germany, with the highest installed wind capacity in Europe, exhibits similar but stronger behaviour (Fig. 3f). The Iberian Peninsula also has notable installed capacity. Overproduction during ScBL and GL (Fig. 3g) partly balances production for all of Europe (cf. Figs. 3e-g). Since Southeastern Europe (Fig. 3h) and Scandinavia (not shown) have comparatively low wind capacity, they barely contribute to Europe-wide generation. Thus high *volatility* in Europe, defined by the difference between the maximum mean generation during AT and the minimum mean generation during EuBL (22.4 GW, or 66% of Europe's 33.9 GW winter mean wind generation), is dominated by capacity in the North Sea region. Although there is meteorological potential for compensating the current shortfall during blocked regimes, the lack of interconnection and of installed capacity in the Balkans and Scandinavia prevent this potential from being fully exploited. Instead, the geographical imbalance of wind farm deployment increases weather regime-dependent volatility for all of Europe. This is particularly problematic as blocked regimes are accompanied by widespread cold conditions with potentially high electricity demand[24] (Methods, Supplementary Fig. 9).

Europe's installed wind capacity of 110 GW in 2015 is projected to increase to 247 GW by 2030[23]. Under the conservative assumption of unchanged average *CF,* winter mean generation is modelled to rise from 33.9 GW in 2015 to 78.2 GW in 2030 (Fig. 4a,b, Supplementary Table 4; Supplementary Discussions 4&5 discuss alternative scenarios using future *CF*s accounting for increased offshore deployment and more efficient turbines). However, the anticipated deployment of new wind capacity predominantly in the North Sea region[23] (Supplementary Fig. 11) has important consequences for weather regime-dependent volatility. While the ratio of volatility and mean generation remains at 66%, in absolute terms it increases from 22.4 GW in 2015 to 51.7 GW in 2030 (Fig. 4d,e). Instead, investing in new capacity based on understanding weather regime-dependent generation patterns can almost entirely eliminate bulk volatility. This is revealed by simulations where all yet-to-be installed capacity is distributed in peripheral regions of Europe (Iberia, Balkans, northern Scandinavia), which are characterized by different inter-regime behaviour than the North Sea. In this hypothetical scenario, mean generation is almost the same, at 76.7 GW (Fig. 4c, Supplementary Table 5), but volatility is reduced three-fold to 15.7 GW (Fig. 4f), i.e., only 20% of mean generation. Production increases during the critical blocked regimes at the expense of reduced production during cyclonic regimes (Fig. 4c,f). A more detailed statistical view on the time-series of Europe-wide wind generation illustrates the intra-annual variations on short (hours to days) and multi-day (days to weeks) timescales (Fig. 5). Seasonal variations alter the overall production level (Supplemental Discussion 6, Supplementary Figs. 13-15). The 5-day moving average (bold in Fig. 5a) represents multi-day variability, which cannot easily be addressed by storage and flexible demand[15,16] and is primarily caused by weather regimes. The balanced deployment scenario strongly reduces this multi-day variability to levels already experienced with the current fleet, yet reaching a similarly enhanced mean production as in the planned scenario (Fig. 5b, right). This results from balancing weather regime-dependent multi-day volatility by widespread deployment across Europe. The larger variability for the full time series (Fig. 5b, left) reflects the remaining short-term fluctuations within each regime. Furthermore, large power swings during regime transitions in the planned scenario (yellow-highlighted, Fig. 5a) could require radical changes to grid management, whereas a balanced deployment limits these ramps[8]. The lower 5th percentile increases by about 10 GW in all seasons reflecting higher fleet-wide minimum output (Fig. 5b). Skewness in the mean distribution of *CF* towards low *CF*s during blocked regimes and a tail towards high *CF*s during cyclonic regimes reflect weather regime-dependent multi-day volatility (black in Fig. 5c). The severe lull during EuBL is apparent with *CF*s frequently below 0.2. Planned deployment in the North Sea region aggravates this problem and separates the *CF* distribution for cyclonic and blocked regimes further (Fig. 5d). However, in the balanced scenario the distributions of *CF* for all weather regimes are similar and shift towards higher *CF*s, indicating that multi-day volatility has been removed leaving only normally-distributed short-term fluctuations, which can more easily be managed by storage and flexible demand[15]. Such a pan-European wind power system would provide a stable output across a wide range of large-scale weather conditions but also requires enhanced transmission[11].

Another option to reduce volatility is to co-deploy wind and solar PV[12–14]. However, current European mean solar generation is substantially lower compared to wind (Supplementary Table 3). Its regime-dependent volatility is anti-correlated with that of wind, but less pronounced, ranging from 32% of mean generation in winter to 5% in summer (Supplementary Discussions 2, 3). The strongest overproduction in winter occurs during EuBL (+1 GW), which is an order of magnitude smaller than the concurrent underproduction for wind (–12 GW). Thus, a tenfold increase of Europe’s installed solar PV capacity would be required to locally balance the power loss in Europe’s current wind fleet during the severe lull in EuBL. This estimate emphasizes that PV cannot simply compensate the weather regime-induced wind volatility (see Supplementary Discussion 3). Further studies are required for designing an optimally balanced electricity system, considering also other generation types, storage, transmission, demand, and costs[9,15,25,26].

Climate change may affect the characteristics and frequencies of weather regimes. The Mediterranean is seen as a climate change “hotspot”[27] where cyclones might become less frequent[28]. Nevertheless, most studies report that mean wind speed will not change under climate change[20,29,30]. Since robust climate change signals occur on a longer time horizon (50-100 years) than renewable energy investments, our considerations based on the current climate will likely be valid for the coming decades.

This study provides a deeper meteorological understanding of multi-day volatility in European wind power output. Atlantic-European weather regimes cause important wind electricity surpluses and deficits in European sub-regions lasting several days to weeks, which are more difficult to address than local short-term fluctuations. Peripheral regions of Europe in Northern Scandinavia, Iberia, and the Balkans exhibit a high potential for enhanced wind electricity generation during severe lulls in the North Sea region. In addition these lulls come along with prevailing cold conditions and therefore high demand[24]. An interconnected European power system combined with future deployment in peripheral regions could therefore be a strategic response to the multi-day volatility challenge and grid management needs imposed by the effects of weather regimes. Moreover, this meteorological understanding might help to better exploit sub-seasonal weather forecasts in the energy sector. Solar PV could have a local balancing effect, but only if large-scale investment increases its capacity tenfold. Our results show that a profound understanding of continent-scale weather regimes can substantially improve wind power supply irrespective of how the rest of the European power system develops.

Methods

Weather regimes. The Atlantic-European weather regime definition is based on standard approaches using empirical orthogonal function analysis (EOF) and k-means clustering[4,5,32]. EOF analysis is performed on the 10-day low-pass filtered geopotential height anomaly (using a 90-day running mean at the respective calendar time as reference climatology) at 500 hPa (*Z500'*) in the domain 80°W to 40°E, 30°N to 90°N. Global data from ERA-Interim[31] at 1° horizontal resolution are used six-hourly from 11.01.1979 to 31.12.2015. We use ERA-Interim for the weather regime definition, as this reanalysis is thought to feature the best depiction of the large-scale circulation. The seasonal cycle in the amplitude of the anomaly is removed prior to the EOF clustering by computing at each grid point the temporal standard deviation in a running 30-day window for each calendar time, and normalizing *Z500'* by the spatial mean of this running standard deviation in the EOF domain. The leading seven EOFs (76.7% of explained variance) are used for the k-means clustering, which is repeated 10 times to test convergence to a stable solution. The optimal number of clusters is seven (Supplementary Fig. 1) based on the criterion that the anomaly correlation coefficient (ACC) between the clusters is below 0.4. This number of regimes is larger than the 4 weather regimes commonly used in previous studies and found to be optimal by various authors[4,32,33] albeit when considering only a specific season, mostly winter. As explained for instance in the Supplement of Cassou[4], Atlantic-European weather regimes have a strong seasonal cycle and are most distinct between winter and summer, with an optimal number of 4 clusters in each season. A novel aspect of our classification is that it allows identifying regimes year-round. These regimes are the winter and summer patterns described in the literature. The GL regime is similar in all seasons, explaining why we find just 7 rather than 8 year-round regimes. The seasonal preference for each regime is reflected in the monthly frequencies (Supplementary Fig. 2), but each of the 7 flow patterns can occur in all seasons. The objective weather regime index[33] I_{wr}, using the projection of the instantaneous *Z500'* to the cluster mean, is computed to derive individual weather regime life cycles. Time steps from 01.01.1985 to 30.06.2016 (the period of available wind and solar photovoltaics (PV) generation data, see below) are attributed to a weather regime life cycle if $I_{wr} > \sigma(I_{wr})$, the period of $I_{wr} > \sigma(I_{wr})$ lasts for at least 5 days, and it contains a local maximum with a monotonic increase/decrease of I_{wr} during the previous/following 5 days. Here $\sigma(I_{wr})$ is the standard deviation of I_{wr} from 01.01.1979 to 31.12.2015; and wr = AT, ZO, ScTr, AR, EuBL, ScBL, GL. Sub-sequent life cycles of the same weather regime are merged if the mean I_{wr} during the duration of the joint life cycle is larger than the threshold $\sigma(I_{wr})$. If the projection I_{wr} to more than one regime fulfils these criteria, the respective calendar time is attributed to the regime with maximum I_{wr}.

NAO index. To analyse the correspondence between the weather regimes and the NAO, we use the daily NAO index of the Climate Prediction Center (CPC) at the National Oceanic and Atmospheric Administration (NOAA, http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.shtml retrieved at 6 December 2016.), based on a rotated EOF analysis of normalized 500 hPa geopotential height anomalies[34]. Note that this NAO definition uses the seasonal varying patterns of the first EOF valid for each calendar month, and weighted for the considered day. In contrast, our weather regime definition uses a constant EOF pattern year-round, based on the leading 7 EOFs. In our data these 7 EOFs explain 76.7% of the variance in *Z500',* whereas the first EOF, which represents the NAO, only explains 19.6%. The mean NAO indices for all days in one of the weather regimes are given in Supplementary Table 1.

Modelled capacity factors. Hourly wind and PV capacity factors (*CF*) are simulated with the Renewables.ninja models[22,23]. A key advantage of this novel dataset is that its quality has been verified through extensive validation against historic measured power output data so the resulting national *CF*s have been improved through bias correction. In addition *CF*s are available for a long 30-year period. The capacity factor is defined as the actual power output or electricity generation P divided by the installed capacity (*IC*; $CF=P/IC$). Simulations cover the EU-28 countries plus Switzerland and Norway, are nationally aggregated for each country, and run from 01.01.1985 to

30.06.2016. We extract meteorological variables for wind speed, air temperature, and solar irradiance from the MERRA-2 reanalysis[35]. MERRA-2 and its predecessor MERRA are widely used for renewable energy applications as they provide hourly fields and winds at different fixed heights[14,26,36–38]. ERA-Interim, used here for the classification of weather regimes, provides only six-hourly fields. Compromising approximations would be required if it were used to simulate wind and PV generation, which vary substantially over short timescales relative to weather regime life cycles.

Wind power capacity factors are obtained by simulating all operating wind farms at their known locations, based on a database of wind farm locations and characteristics[23] as of 2015 (known sites on the 1.1.2015, which we call "Current" system). In addition, wind farms currently under construction or with planning approval and expected online by 2020 (called "near-term" in Staffell and Pfenninger[23]) as well as those earlier in the planning process ("long-term" in Staffell and Pfenninger[23]) expected online by 2030 are simulated to obtain a view of generation profiles if wind deployment proceeds as currently underway and planned.

PV power generation is simulated by assuming a 1 kW PV installation in each grid cell of MERRA-2, which have a size of 0.5° latitude times 0.625° longitude. Unlike for wind farms, the exact location and configuration of all current PV installations is not known, and so panel angles (tilt and azimuth) are drawn from a normal distribution according to the known panel angles from a database of PV installations in Europe[22].

Measured generation data. In addition to the bias-corrected modelled capacity factors described above[22,23], observed time-series of nationally aggregated wind and PV capacity factors are obtained by using data from several transmission system operators (TSOs; see Supplementary Discussion 7, Supplementary Figs. 16-19, Supplementary Table 7). These time-series are used to verify our results with an independent data set (Supplementary Discussion 7). TSOs provide power output data, which were matched to installed generation capacity to obtain capacity factors. Installed generation capacity is reported by the TSOs in Germany and the UK. For the other countries, we use the mean capacity from three sources: Eurobserv'Er[39], BP[40] and EnerData[41]. These three sources report end-of-year installed capacity per country, which we interpolate with a third-order spline to produce an estimate of continuous capacity development throughout each year. These capacities can only serve as estimates, and do not necessarily reflect the amount of capacity being monitored by each TSO. However, we focus on variability over multi-day timescales, which is unaffected by inter-seasonal discrepancies in capacity statistics. In each country, we examine the resulting capacity factor time-series for systematic issues (peak CF above one, systematically rising or falling, or average CF deviating from known values). In those cases, we apply a linear correction to our estimate of capacity.

Mean capacity factors during the seven weather regimes. A mean country-specific capacity factor $CF_{wr,country,season}$ is computed using all time steps attributed to one of the seven regimes (AT, ZO, ScTr, AR, EuBL, ScBL, GL) and to no regime, and stratified according to the four seasons (winter: DJF, march: MAM, summer: JJA, autumn: SON). In addition, seasonal mean country-specific capacity factors $CF_{country,season}$ are computed. We also discuss an alternate measure: the relative change in electricity generation $\Delta CF_{wr,country,season}$ (see Fig. 1). This measure is defined as the ratio of the difference in mean generation in a regime with respect to the seasonal mean generation in %, e.g. for winter, $\Delta CF_{wr,country,DJF} =(CF_{wr,country,DJF} - CF_{country,DJF}) / CF_{country,DJF}$.
Mean power generation during a regime $P_{wr,country,season}$ is defined as the product of a country's installed capacity $IC_{country}$ and $CF_{wr,country,season}$ $(P_{wr,country\ season} = IC_{country} * CF_{wr,country,season})$. We refer to "regime-dependent volatility in mean generation" as the difference between the mean generation in the regime with maximum and minimum mean generation

$(max(P_{wr,country,season})-min(P_{wr,countryseason}))$.

Region aggregation and scenarios. To consider CF (Fig. 3a), ΔCF (Fig 1, inset), and P for all of Europe we spatially aggregate based on the country-specific $CF_{wr,country}$ (subscript "*season*" omitted for brevity):

- Capacity factors are weighted by the land area "$a_{country}$" of a country

  $CF_{wr,Europe} = \Sigma(CF_{wr,country} * a_{country})/a_{Europe},$

  $a_{Europe}=\Sigma\, a_{country},$

  where wr=AT, ZO, ScTr, AR, EuBL, ScBL, GL, no regime.
- $\Delta CF_{wr,Europe} = (CF_{wr,Europe} / CF_{Europe} - 1).$
- Installed capacity (IC), and total production are summed up

  $P_{wr,Europe} = \Sigma(CF_{wr,country} * IC_{country}),$

  $IC_{Europe}=\Sigma\, IC_{country}.$

Significance is tested for $P_{wr,country,season}$ vs. $P_{country,season}$ using a two-sided student t-test. For all scenarios and seasons, all values of $P_{wr,Europe,season}$ are significant at the 5% level except for no regime conditions in the balanced scenario in summer (Supplementary Fig. 14).

The area weighting of CF for Europe (inset Fig. 1, Fig. 3a) takes into account that the country-specific CF represents the potential for renewable electricity production in an entire country (neglecting details such as population density, terrain, or coastal area), such that the aggregated CF is proportional to the relative fraction of the countries' area. Thus the aggregated CF represents the hypothetical potential for Europe-wide generation if IC was distributed equally over Europe. However, for the actual area-aggregated production P we have to sum up without area averaging to yield the real production. We also construct a time series of six-hourly European production and discuss their statistics (Fig. 5, Supplementary Figs. 13-15).

For the hypothetical "2030 Balanced" scenario of future wind farm deployment in peripheral regions of Europe (Fig. 4c,f, Supplementary Table 2), we distribute the 137 GW yet-to-be-installed capacity as follows: Iberia +30 GW (+5 GW in Spain, +25 GW in Portugal), northern Scandinavia +40 GW (+20 GW in Norway, +20 GW in Finland), Balkans +67 GW (+42 GW in Greece, +10

GW in Bulgaria and Croatia each, +5 GW in Slovenia). This scenario demonstrates an even distribution of installed capacities across European sub-regions with contrasting inter-regime behaviour, but is not the result of formal optimization. Such a scenario would also require an expansion of transmission capacities from peripheral regions to load centres and a larger interconnection of the European electricity transmission system. Supplementary Discussions 3&4 discuss the sensitivity of future scenarios on wind farm deployment in more detail.

To compare the frequency distribution of six-hourly production for the different scenarios we show histograms of the actual Europe-wide $CF^{*}_{wr,Europe}$ weighted by installed capacity (Fig. 5c-e): $CF^{*}_{wr,Europe} = P_{wr,Europe} / IC_{Europe}$.

Modulation of near-surface weather during different regimes

The different weather regimes are accompanied by important changes in near-surface wind and therefore also modulate potential wind power output (Fig. 1 and Fig. 2). In addition, the weather regimes modulate 2 m temperatures (Supplementary Fig. 9) and therefore have a potential impact on electricity demand[24,42], assuming that cold conditions in winter increase demand. During the three cyclonic regimes, the specific location of a low-pressure system in the North Atlantic governs this behaviour (Fig. 2a-c). During AT the comparatively southern location of the low enhances wind speed in Western Europe (Fig. 2a) and continental Europe experiences mild conditions (Supplementary Fig. 9). During ZO a strong Icelandic low enhances wind speed in Scandinavia, the North and Baltic Seas (Fig. 2b) and vast parts of Central, Eastern, and Northern Europe experience mild conditions (Supplementary Fig. 9). During ScTr low pressure over Scandinavia enhances wind speed in Britain, Central, and Eastern Europe (Fig. 2c) while Eastern Europe experiences mild conditions (Supplementary Fig. 9). Southern Europe is affected differently during the cyclonic regimes. Whereas wind speeds are also enhanced in Iberia during AT, the Azores anticyclone extends to the Mediterranean during ZO and ScTr, leading to calm conditions there. ScTr favours

Mistral winds in Southern France, with northerly flow encompassing Corsica, Sardinia, and western Italy. Rather cool conditions prevail in Iberia (Supplementary Fig. 9).

The four blocked regimes strongly reduce near-surface winds and temperatures (Fig. 2d-g, Supplementary Fig. 9), but enhanced winds occur at the flanks of the stationary anticyclones due to enhanced cyclonic activity there. During AR (Fig. 2d, Supplementary Fig. 9) this occurs in Northern Scandinavia and in the Mediterranean, where Mistral and Bora winds further increase wind speed. However, cold conditions prevail in all of Europe. During EuBL, cold temperatures prevail over continental Europe in particular France, Central and Eastern Europe, and the Balkans, while the North Atlantic region experiences mild conditions (Supplementary Fig. 9). Weak winds extend over vast parts of Europe in particular the North Sea region (Fig. 2e). However, the peripheral regions of Northern Scandinavia and the Balkans experience enhanced winds. Specifically the cold Bora affects Slovenia and Croatia, whereas cold winter Etesians in the Black and Aegean Seas affect Greece, Bulgaria, and Romania. Both the ScBL and GL regimes (Fig. 2f-g) reduce winds in Northern and Central Europe accompanied by extremely cold conditions in Eastern and Central Europe, and Central and Northern Europe, respectively (Supplementary Fig. 9). Concurrent cyclone activity in the western Mediterranean enhances wind speed and temperatures there. In addition, easterly flow in the Balkans during ScBL favours Bora winds. 23% of the winter days cannot be attributed to a regime. They exhibit no flow and no temperature anomalies on average and are therefore not relevant for multi-day wind generation variability (Fig. 2h) and do not lead to anomalous demand.

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Data Availability. Data presented in the manuscript are available from https://www.renewables.ninja/downloads[22,23] and ECMWF[31] (http://apps.ecmwf.int/datasets/data/interim-full-daily).

The combined weather regime and wind/solar PV data, ICs, $a_{country}$, $CF_{wr,country,season}$, and $CF_{country,season}$ are provided in Supplementary Data 1.

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Author contributions CMG led the study, provided the weather regime classification and plotted the data. CMG and SP did the bulk of writing. RB, SP, and IS processed the data. HW initiated the collaboration of CMG and RB and early links with the ETH Climate Policy Group. All authors contributed equally to editing and discussing the manuscript.

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Figure legends

Figure 1. Weather regime-dependent change in wind electricity generation. Country-specific relative change of *CF* during cyclonic regimes (red labels, inset), blocked regimes (blue labels), and no-regime times (grey) shown as percent deviations ($\Delta CF_{wr,country}$) from winter mean. $\Delta CF_{wr,country}$ is the normalized difference of the country-specific mean *CF* during a weather regime to the whole winter mean ($\Delta CF_{wr,country}=(CF_{wr,country}-CF_{country,DJF})/CF_{country,DJF}$) and indicates the potential over- or underproduction during a specific regime. Barplot labels indicate country ISO code and 2015 installed capacity (in GW). Shading: winter mean (DJF 1979-2015) wind speed 100 m above ground (m s^{-1}). Inset: $\Delta CF_{wr,country}$ for Europe with axis labels. Each bar corresponds to a weather regime coloured as follows: purple AT, red ZO, orange ScTr, yellow AR, light green EuBL, dark green ScBL, blue GL, grey no regime. Values above the winter mean (overproduction) are shown in dark, and values below the mean (underproduction) in light colours.

Figure 2. Wind anomalies during weather regimes. 100 m wind speed anomalies (blue-red, m s^{-1}), absolute wind at 100 m (grey vectors), and mean sea level pressure (contours every 10 hPa) in winter for each regime (a-g), no regime (h), and whole winter (i), with regime frequencies in % and mean NAO index (inset). Country-specific barplots from Fig. 1, with relevant regime coloured. L and H labels indicate centres of low and high-pressure systems. Panel captions indicate names of cyclonic regimes in red and of blocked regimes in blue.

Figure 3. Capacity factors and wind power output in winter. (a-d) country-specific mean capacity factors *CF* for winter days (DJF, 1985-2016) in the regimes (coloured bars: purple AT, red ZO, orange ScTr, yellow AR, light green EuBL, dark green ScBL, blue GL, grey no regime; red labels cyclonic, blue labels blocked, grey label no regime). Dark colours highlight portion above whole winter mean (horizontal line), light colours portion below. (e-h) mean wind electricity generation *P* (GW) in a regime, not to be confused with instantaneous output. 1 GW is approximately the generation of a nuclear power plant. Bar widths scaled with regime frequency (see Fig. 2). Note the different y-axis scale for (f-h) compared to (e).

Figure 4. Future European wind power output in different scenarios. (a-c) Wind power output *P* (in GW) as in Fig. 3e and (d-f) absolute difference in *P* (in GW) to whole winter mean for each regime (coloured bars: purple AT, red ZO, orange ScTr, yellow AR, light green EuBL, dark green ScBL, blue GL, grey no regime; red labels cyclonic, blue labels blocked, grey label no regime). Dark colours highlight portion above whole winter mean, light colours portion below. (a,d): "Current" scenario with installed wind capacity as of 2015, (b,e): planning for 2030, (c,f) alternate "Balanced" scenario for 2030 with new capacity deployed in peripheral regions of Europe.

Figure 5. Time series of European wind power output. (a) Example time series showing the total wind power output of all European wind farms during one season based on weather conditions from winter 1992/93. Lines relate to the "Current" fleet as of 2015 (black), the "2030 Planned" scenario (orange), and the "2030 Balanced" scenario (green). Thin lines show the six-hourly output and thick lines the 5-day centred moving average. The coloured bar on the horizontal axis indicates the regime classification over the period (see legend). The yellow transparent box highlights a regime transition with a sudden decrease of mean production, which is particularly pronounced in the "Planned" scenario. (b) Box and whisker plots summarizing the winter (DJF) variability from 1985-2015 in six-hourly (left) and the 5-day averaged (right) wind generation for the three scenarios (coloured as in a). Box shows the lower and upper quartile and median, whiskers the 5th and 95th percentiles, dot the mean, and crosses the mean ± one standard deviation. (c-e) Frequency distribution of six-hourly European wind production normalized by Europe-wide installed capacity ($CF^{*}_{wr,Europe}$) for winters from 1985-2015 attributed to a weather regime (colours as in a), no regime (gray), and all winter times (black). Blocked regimes highlighted with dashed lines. Bin width is 0.05. The vertical black dashed (solid) line shows the median (mean) for all winter times. In contrast to Fig. 1 (inset) and Fig. 3a, $CF^{*}_{wr,Europe}$ is here simply weighted by Europe-wide installed capacity, to reflect the actual production in Europe's wind fleet rather than its hypothetical production potential (see Methods).