REVIEW

Extreme Weather Events and the Energy Sector in 2021

JUAN A. AÑEL,[a] CELIA PÉREZ-SOUTO,[a] SUSANA BAYO-BESTEIRO,[a,b] LUIS PRIETO-GODINO,[c,d] HANNAH BLOOMFIELD,[e] ALBERTO TROCCOLI,[f,g] AND LAURA DE LA TORRE[a]

[a] EPhysLab, CIM-UVigo, Universidade de Vigo, Ourense, Spain
[b] Institute for Systems and Computer Engineering, Technology and Science, Porto, Portugal
[c] Global Technical Services, Iberdrola Renovables Energía, Madrid, Spain
[d] Department of Signal Processing and Communications, Universidad de Alcalá, Alcalá de Henares, Spain
[e] School of Engineering, Newcastle University, Newcastle upon Tyne, United Kingdom
[f] School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
[g] World Energy Meteorology Council, The Enterprise Centre, University of East Anglia, University Drive, Norwich, United Kingdom

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ABSTRACT: In 2021, the energy sector was put at risk by extreme weather in many different ways: North America and Spain suffered heavy winter storms that led to the collapse of the electricity network; California specifically experienced heavy droughts and heat-wave conditions, causing the operations of hydropower stations to halt; floods caused substantial damage to energy infrastructure in central Europe, Australia, and China throughout the year, and unusual wind drought conditions decreased wind power production in the United Kingdom by almost 40% during summer. The total economic impacts of these extreme weather events are estimated at billions of U.S. dollars. Here we review and assess in some detail the main extreme weather events that impacted the energy sector in 2021 worldwide, discussing some of the most relevant case studies and the meteorological conditions that led to them. We provide a perspective on their impacts on electricity generation, transmission, and consumption, and summarize estimations of economic losses.

KEYWORDS: Extreme events; Climate change; Renewable energy

1. Introduction

The report published by the Intergovernmental Panel on Climate Change in August 2021 defines an extreme weather event as "an event that is rare at a particular place and time of year" (Seneviratne et al. 2021). It is well known that extreme weather has huge socioeconomic impacts (Lazo et al. 2020; Liu et al. 2020) and that climate change is exacerbating it (Clarke et al. 2022). The study of extreme weather events (EWEs) has become a research field in itself, and the *Bulletin of the American Meteorological Society* has been publishing the annual series "Explaining Extreme Events" since 2012 (Peterson et al. 2012). Although weather attribution science is now done in a rapid way, most of the academic work analyzing EWEs for 2021 has begun to appear only recently.

The energy sector is critical in our society. Worldwide energy consumption increases steadily each year (International Energy Agency 2021b), surpassing now 400 EJ. This consumption and electricity production are heavily connected to weather and climate (e.g., renewable generation, water availability and temperature for thermal power plants) (Troccoli et al. 2014; Añel 2015), transport, and demand (Baker 1985). All these activities are tied to polluting emissions (CO_2, CH_4, etc.) and, therefore, to anthropogenic climate change, and poor air quality, which eventually result in health issues and economic impacts (Im et al. 2018). Because of this, understanding the relationship between weather and the energy sector is key: better knowledge and more awareness will lead to improvements in the way we can adapt to climate change.

The impact of extreme weather on the energy sector is evident and has been reviewed in the literature (e.g., Troccoli et al. 2010; DOE 2013; Añel et al. 2017; Jackson and Gunda 2021). When it comes to energy production, geographical location matters, and different regions of the world suffer different types of EWEs. The viability of a power generation plant must take into account this type of event, whether it is a crude extraction well or a hydropower station.

For example, high temperatures increase the resistance of power transmission lines and increase power losses (Bartos et al. 2016). High temperatures also affect generation by reducing the efficiency of gas- and oil-based generation plants.

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Corresponding author: Juan A. Añel, j.anhel@uvigo.gal

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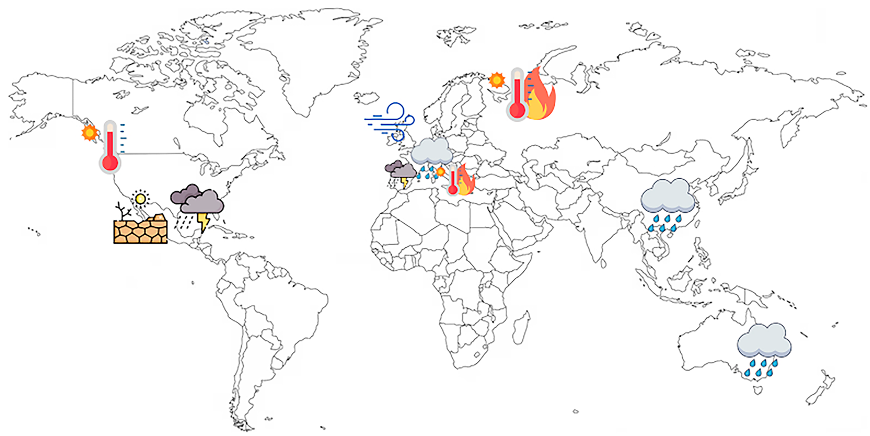

FIG. 1. Global distribution of the events studied here.

Situations can also be induced in which generation must be stopped due to being above the temperature limit thresholds allowed for a generation facility. Such incidents have happened in recent years in France with nuclear power plants due to excessively warm temperature of the water used for cooling. This phenomenon is becoming more frequent due to climate change and could cause an average annual generation loss of up to 2.4% by the end of this century (Ahmad 2021). Low temperatures, heavy snow, and ice buildup can cause icing of wind turbines and the failure of overhead lines and transmission towers, causing disruptions to the power grid. They can also reduce electrical output by causing electrical breakdowns. Strong winds during storms can cause failure and damage to the overhead transmission and distribution lines, either by collapsing distribution towers or by debris falling on the lines (Donaldson et al. 2023). On the other hand, prolonged periods of calm wind conditions negatively affect generation by limiting wind production. Flooding during storms can also impact substations. Therefore, improved resilience of power generation plants is necessary to reduce weather- and climate-related risks. The study and knowledge of the relationships between meteorology, energy production, and the power system components make it possible to face situations (foreseen or not) more efficiently, optimizing generation resources (Dubus et al. 2018). For this reason, a better understanding of the influence of weather in the energy sector will result in a better ability to forecast supply and demand.

Here, we provide evidence of the relevance of this relationship by analyzing the EWEs that happened in 2021 and how they affected the energy sector. In 2021, 350 million people worldwide were affected by major energy outages (World Economic Forum 2023), many of them caused by a few remarkable meteorological phenomena. Cold waves in Texas and Spain were especially relevant, as were extreme floods in Australia, central Europe, and China. There was a heat wave in the Pacific Northwest of North America, concurrent with a heavy drought in California and wildfires from May to October. Other less studied phenomena, such as a wind drought in Europe, were relevant too. Data are also from private companies in a sector for which access to and publication of this type of information is not easy. We do not cover "regular" hurricanes, tornadoes, monsoons, or typhoons here; instead we focus on unusual high-impact EWEs that do not happen annually.

The following sections outline the method used and provide examples of various cases of EWEs that have impacted different parts of the energy sector. This aims to give an overview of the different types of EWEs that have occurred during 2021, attempting to integrate meteorological factors with their societal impacts; such an integration is not commonly found in current literature.

2. Method

We performed an extensive search for EWEs in 2021 that impacted the energy sector. To do this, we used an already-tested method for searches using keywords (Bayo-Besteiro et al. 2022) and search engines (Google and Google Scholar). Figure 1 and Table 1 list some of the most remarkable EWEs impacting the energy sector in 2021. We have chosen these case studies based on the rationale of the representativeness of different meteorological phenomena associated with different variables. In this way, we present temperature-related phenomena (both cold waves and heat waves), precipitation (including snow and floods), and wind. This allows us to provide a broad picture of different extreme phenomena occurring throughout the year in different seasons. Also, selecting these events provides comprehensive geographical coverage, showing impacts all around the Northern Hemisphere. Last, we consider that including a wind drought in our analysis is of utmost relevance, as it is a phenomenon of great importance for the energy transition, barely studied in the literature and especially striking in 2021.

3. Case studies

a. *Filomena and Uri winter storms*

The beginning of 2021 featured two major winter storms, separated by one month and in different parts of the Northern Hemisphere. The first one was Filomena, which affected the

TABLE 1. Extreme weather events with associated energy impacts in 2021, including the region affected, dates of occurrence, impacts, and published works with information on them. The events in boldface are the ones reviewed here. The list is not exhaustive and only includes those works with the most relevant information to this paper.

Type of event	Region affected	Dates	Impacts	Related works
Winter storm Filomena	Central Spain	8–17 Jan	Power lines down and need to balance the energy mix	AEMET (2021a), Tapiador et al. (2021), Smart (2021), P. Zschenderlein and H. Wernli 2022 (unpublished manuscript, available at https://doi.org/10.5194/nhess-2021-396), Faranda et al. (2022), Hou et al. (2023)
Winter storm Uri	Texas	10–20 Feb	Severe problems in generation; frozen pipelines	Busby et al. (2021), Doss-Gollin et al. (2021), FERC (2021), Mann et al. (2021), Popik and Humphreys (2021), Albers et al. (2022), Bolinger et al. (2022), Davis et al. (2022), Gruber et al. (2022), Lee and Dessler (2022), Levin et al. (2022), Millin and Furtado (2022)
Drought in California	California	Feb–Nov	Reduction in hydropower production	Hoell et al. (2022)
Floods in Australia	Eastern Australia	17–26 Mar	Damage in power infrastructure	Australian Institute for Disaster Resilience (2021), NASA (2021), Reid et al. (2021), Kelly and Kuleshov (2022), Wert et al. (2023)
U.K. wind drought	West Europe	Apr–Sep	Decrease in wind power production	ECMWF (2022), Kay et al. (2023)
Pacific Northwest heat wave	Pacific Northwest America	Jun–Jul	Damage in power infrastructure and power outages	Overland (2021), McKinnon and Simpson (2022), Philip et al. (2022), Schumacher et al. (2022), White et al. (2023), Loikith and Kalashnikov (2023), Heeter et al. (2023)
Central Europe floods	Central Europe	12–19 Jul	Stops in power generation; 200 000 people without power; damage in infrastructure and power outages	Eurelectric (2022), Koks et al. (2022), Mohr et al. (2023), Ludwig et al. (2023)
Heat wave/ wildfires	Siberia	Jul–Aug	Endangered hydropower plant	Copernicus Atmosphere Monitoring System (2021), Scholten et al. (2022)
Heat wave/ wildfires	Greece	Jul–Aug	Excess electricity demand; limitations to electricity consumption	Founda et al. (2022), Giannaros et al. (2022), Fuckar et al. (2022)
Floods in Shanxi	Northeast China	1–14 Oct	Coal mine closures, stress in the supply chain, and worldwide increase of coal prices	Che et al. (2021), Feng et al. (2022), Liu (2022), Zhou et al. (2022), Gu et al. (2022), Hu et al. (2023)

Iberian Peninsula. The other one was "Uri," which affected several North American states, but especially Texas. Uri is now probably one of the best-studied EWEs with impacts on the energy sector because of the significant shocks it produced, including deaths. Common to both of these storms were heavy snow accumulation and freezing weather. The relationship with climate change in these episodes is unclear; however, it is known that, for the case of Uri, the estimations of the Electric Reliability Council of Texas (ERCOT) about peak electricity demand clearly underestimated the risks that winter storms pose in the current scenario of climate change and EWEs (Lee and Dessler 2022).

1) METEOROLOGICAL CONTEXT

The meteorology associated with Filomena has been well explained by the Spanish Meteorological Agency [Agencia Estatal de Meteorología (AEMET 2021a)]. It was an extratropical cyclone in origin that formed on 1 January near the U.S. East Coast, experienced an excursion to subtropical latitudes near the Canary Islands, and then, with moistened air, moved north to the Iberian Peninsula. In this sense, Filomena was different from the usual snow episodes on the Iberian Peninsula, which are typically associated with excursions of cold polar air masses. On 8 and 9 January, the warm moist air that Filomena brought after its subtropical excursion, extended over cold polar air previously brought over the Iberian Peninsula. As a result, snow depths of 0.30–0.53 m were recorded (AEMET 2021b). After it, a cyclone situated over the Iberian Peninsula produced a cold spell for one additional week, with temperatures plummeting to values ranging between −2° and −26.5°C (and lower at unofficial stations), the lowest recorded in the previous 20 years (AEMET 2021a; Smart 2021). Figure 2 shows the anomalies of the mean 2-m temperature for 7–10 January 2021 and the historical records of 4-day accumulated snowfall, putting into context how extraordinary Filomena was.

The meteorological conditions associated with Uri have been explained too, and the U.S. National Weather Service has published a good account of it (NWS 2021). On 10 February, a cold front moved over Texas, and 3 days later an Arctic cold front reached the region too. The situation evolved to precipitation in the form of snow and sleet and freezing temperatures between 14 and 16 February. Without these conditions ending, another winter storm with freezing rain joined, worsening the conditions, which lasted 4 days more. However, the situation is acknowledged to have had a stratospheric precursor, and it has been shown that vertically propagating Rossby waves disrupted the stratospheric polar vortex (Liberato et al. 2007; Castanheira et al. 2009; Millin and Furtado 2022), ending in a major sudden stratospheric warming (SSW) (Lee 2021; Lu et al. 2021). The weakening of the stratospheric polar vortex allowed cold polar air and high pressures to establish over Canada and then move southward because of the wavy behavior of the jet stream (Bolinger et al. 2022). In addition, it resulted in a negative pattern of the Northern Annular Mode (NAM), usually associated with major SSWs and cold episodes over North America (de la Torre et al. 2006; Lee 2021) as well as a cold pattern (phase 7) of the Madden–Julian oscillation (MJO) affecting the region (Lu et al. 2021). Moreover, it has been shown that existing La Niña conditions favored the event (Albers et al. 2022).

Recent research has suggested that the temperature extremes combined with their duration have return periods exceeding 50 years (Doss-Gollin et al. 2021; Albers et al. 2022). Although these events are unusual in Texas, making it difficult to establish a trend, climate change is not expected to favor them (Nielsen-Gammon et al. 2021).

2) Consequences

For the storm Filomena, in the region of Castilla-La Mancha (southeast of Madrid, Spain), up to 27 000 clients suffered blackouts because of fallen transmission lines (Fresneda 2021), although most of these were minor incidents, and only a few remained without electricity for up to four days (RTVE 2021). On the other hand, despite the cold weather, low solar power production, high natural gas prices, and the associated

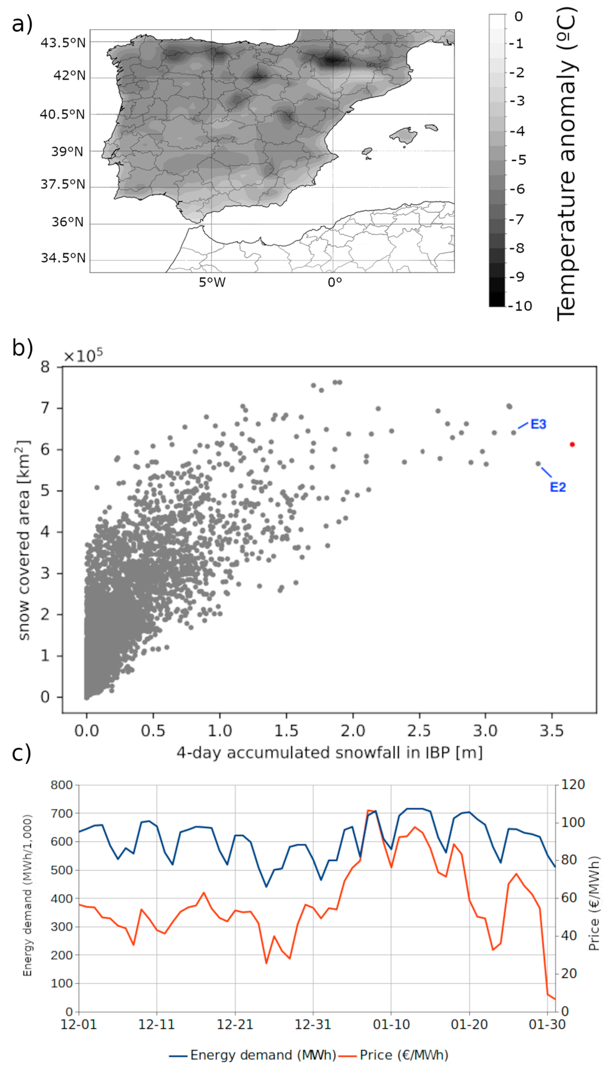

FIG. 2. (a) Anomalies (°C) of the mean 2-m temperature for 7–10 Jan 2021 with respect to the historical mean (1979–2019) for the same days; data are from the ERA5 reanalysis hourly means (Hersbach et al. 2020). (b) Four-day accumulated snowfall vs snow-covered area of all winters from 1979 to 2019 in the Iberian Peninsula (IBP). The red point represents the period 7–10 Jan 2021 (Filomena), label E2 marks the period 2–5 Jan 1997, and E3 marks the period 28–31 Jan 1986 [the plot is from P. Zschenderlein and H. Wernli 2022, unpublished manuscript, available at https://doi.org/10.5194/nhess-2021-396]. (c) Evolution of the demand and prices of electricity in Spain for the month before and after Filomena. Source: Red Eléctrica Española.

high demand for electricity that brought rising prices (Fig. 2), wind farms contributed substantially, with peaks of power production covering up to 47% of the electricity demand in the country (REVE 2021).

Despite this, during Filomena, the Spanish electricity system showed remarkable resilience, with only 50 incidents reported on transmission lines, mainly in the center of the Iberian Peninsula. Increases in demand were up to 13% relative to previous weeks. However, these were satisfied by energy imports from other countries (Red Electrica Española 2021). There is no estimation of costs specific to the energy sector beyond the impact on the prices of electricity, which were prohibitive for many people; however, Filomena caused an estimated 1.2 billion U.S. dollars of damage (AON plc 2021).

In the case of Uri, the load on the electricity system increased from around 40 GW to over 70 GW. This marked the highest winter peak demand recorded in Texas and the first time when the state experienced a greater winter than summer peak demand (Skiles et al. 2023). Uri resulted in a shortage of power generation, the need for rolling blackouts that affected more than 4 million people (some extending up to four days), and prices spiking around \$9,000 $(\mathrm{MW\ h})^{-1}$. The shortage of power production was a consequence of the incorrect estimation of the generation capacity by ERCOT (Busby et al. 2021; Lee and Dessler 2022), frozen coal and gas power plants, gas supply infrastructure, and water pumps in nuclear power stations (U.S. Nuclear Regulatory Commission 2021) after temperatures reached below −8.8°C and down to −10.9°C (Gruber et al. 2022). Nearly 20% of the total U.S. refinery capacity was shut down (DOE 2021). The economic cost of the power outages and disruptions in Texas has been estimated in a range between 26.1 and 130 billion U.S. dollars (Puleo 2021; NOAA/National Centers for Environmental Information 2023).

b. *Pacific Northwest heat wave and drought*

Prolonged drought conditions have been suffered in California several times over the last three decades. Some have lasted multiple years such as from 2012 to 2015 (Olsen et al. 2023) (and references therein). Southwestern North America is a region that has been proven to be historically prone to megadrought (drought events of exceptional length) conditions, and climate change exacerbates them (Williams et al. 2020). Also, EWEs have led to substantial socioeconomic impacts in this region of the world. In 2021 the Pacific Northwest suffered an episode of drought that lasted nearly a year, combined with heat-wave conditions over the summer (White et al. 2023). In this region, 2021 was the hottest year of the last millennium (Derouin 2023). The city of Sacramento, California, broke its record for consecutive days without rainfall, with 211 days, and Death Valley recorded the highest temperature on Earth since 1930 (WMO 2022). Moreover, compound EWEs are recurrent now in California (Pu et al. 2022), and the region faces worsening conditions of drought and heat waves under climate change. Recent research has estimated that these extended conditions over 2020 and 2021 increased sixfold because of anthropogenic climate change and La Niña conditions (Hoell et al. 2022).

1) Meteorological context

The meteorological situation for this event has now been well described in the literature, especially for the heat wave during June–July 2021 (Overland 2021; McKinnon and Simpson 2022; Schumacher et al. 2022; White et al. 2023). An omega-blocking situation developed; however, this was not enough to explain the extraordinary situation, where the dryness of the soil played a key role, and the transport of latent heat contributed to warming the middle troposphere (Schumacher et al. 2022). The 500-hPa geopotential height was greater than usual, with peak values over British Columbia, Canada (Loikith and Kalashnikov 2023). A Canadian national maximum temperature record was set in Lytton, British Columbia, on three consecutive days (27–29 June), peaking at 49.6°C. According to the U.S. Drought Monitor (USDM; see Fig. 3), the drought conditions in California began in February 2021 with a D0 category (abnormally dry) and worsened through the year, reaching a D4 value (exceptional drought) by the end of November 2021, when conditions began to improve. The compound interaction of heat waves and drought has been pointed out, suggesting that the dry conditions, with low evapotranspiration, were also crucial for the extreme heat during June (Philip et al. 2022).

Additionally, several wildfires happened: In British Columbia, by late June and early July, after those days of extreme heat, dry storms and more than 700 000 lightning strikes sparked more than 180 wildfires. In Beckwourth (Plumas County, California), lightning also caused another wildfire, which lasted from 2 July to 1 August. Another one, the Dixie Fire, began on 13 July, expanded through five counties, and merged with the Fly wildfire on 22 July. This merged wildfire lasted until 30 October, burning 187.562 ha, the second-largest wildfire ever recorded in California. The Bootleg wildfire (Beatty, Oregon) began on 6 July and was contained on 1 October, burning an area of 1674 km^2 and had days of generating pyrocumulus and therefore, its own weather (Amici et al. 2022).

2) Consequences

The drought led to a significant reduction in hydropower production. In 2020 the generation from this source in California was 13.6% of California's total power mix, which was 44% lower than in 2019 (California Energy Commission 2021a), and then in 2021 was even lower, at 10.2%. The water storage levels in reservoirs in California were very low. The Oroville Reservoir (Butte, California) was below average throughout the hydrological year (see Fig. 3), reaching values below 30% by June, and staying at such low levels until January 2022. The Hyatt hydropower station (which the previous year had supplied 60% of the power for Butte County, California) was stopped for the first time since it became operational in 1968, because Lake Oroville reached values of approximately 35% of its storage capacity and 45% of its historical average, the minimum levels under which the station can operate. The station became operational again on 4 February 2022 (L. Whitmore, California Department of Water Resources, 2021, personal communication). A side effect was that the deficit of hydropower generation was covered with natural gas.

During the wildfire in Lytton, 90% of all the structures, including power stations, were destroyed. This occurred during a peak in demand for electricity, mainly for air conditioning (Beugin et al. 2023). During the Bootleg wildfire, several

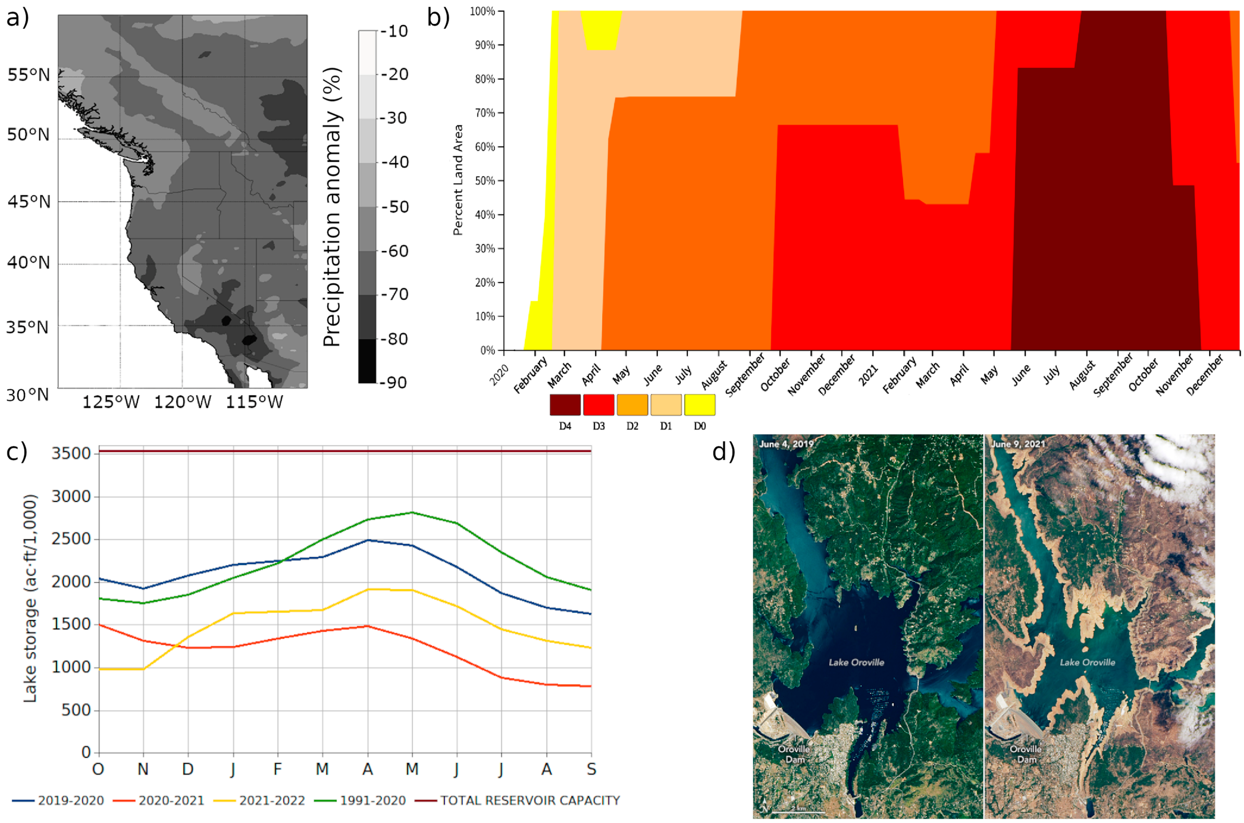

FIG. 3. (a) Anomaly of mean annual precipitation in western North America for 2021 relative to the historical mean for 1971–2020 (values over the ocean are not plotted). The data source is ERA5 monthly mean total precipitation. (b) Drought index for Butte County (% of the county under drought conditions) for 2020–21; darker colors are indicators of greater drought level. Source: USDM. (c) Lake Oroville storage levels from October 2020 to September 2022 (in acre feet; 1 acre ft = 1233.5 m^3). The blue line shows the historical mean storage. Source: California Department of Water Resources. (d) Satellite view of Oroville Lake on (left) 4 Jun 2019 and (right) 19 Jun 2021. The images are from *Landsat-8*, provided by the NASA Earth Observatory.

transmission lines supplying power to California were destroyed (Amici et al. 2022). The most significant problems happened on 8 July. On this day, the California power network was saturated (and exacerbated by the fact that a gas power station (Russell City Power Center), with a capacity to supply 600 000 homes, became inoperative on 27 May after an explosion), on the brink of scheduled rotating outages. Three lines of the Oregon–California interconnection network fell, reducing the imported energy by 4000 MW (almost 10% of the peak demand on that day) (California Energy Commission 2021b). The capacity transported by the Pacific DC Interconnection, which runs through the state from north to south, also had to be limited to prevent that line from suddenly falling. Due to this, the deficit between the available energy and the peak demand rose to 5500 MW.

During the nights (without solar power production), hydropower was used; however, its availability was limited because of the drought. Lithium-ion batteries that stored energy from solar power were used, providing between 500 and 1000 MW over several hours. However, it was not enough, and a state of emergency was declared, asking private utility companies to prepare for continued blackouts. Air pollution requirements were relaxed to let utilities resort to other fossil sources, such as diesel backup generators, during grid stress. Measures such as constructing temporary gas plants and improving existing ones were approved to deal with the continuous energy shortage. At the same time, the California Independent System Operator (CAISO) called on the public to reduce power consumption at peak demand hours when price spikes were expected. Also, the primary generation sources (natural gas and nuclear plants) did not fail, and by relying on nonrenewable sources, rotating blackouts were avoided. However, some renewable energy curtailments were necessary because of the instability in power. During this situation, it was feared that the same thing would happen as the previous year, 2020, when CAISO was forced to make rotating blackouts during a heat wave on 14–15 August (which affected some two million customers). In that case, some industries had to stop operating because of outages. Also, there was an economic impact on clients, as electricity prices in California reached \$1,500 $(MW\ h)^{-1}$ on 16 August 2021 (CAISO 2021).

In British Columbia, record-breaking temperatures also triggered a record power demand. According to the British Columbia Hydro and Power Authority (BC Hydro), on 28 June, all-time records for peak summer demand were broken, with a peak of 8568 MW (600 MW more than the previous peaks) and 35% higher than the seasonal average. The unplanned outages because of excess demand skyrocketed on 28 June, reaching 400 outages and affecting more than 40 000 customers, as compared with a daily average in the week before the heat wave of around 50 outages with 1000 customers affected. The resilience of the British Columbia power production system (where 80% of energy production comes from hydropower plants and which had not experienced severe droughts in many years) meant that the increase in demand did not imply significant changes in energy production, nor did it have to resort to nonrenewable sources, which could have worsened the situation.

Without specific estimations about the economic impact on the energy sector, it is estimated that the drought cost about 9.1 billion U.S. dollars, and wildfires from June 2021 accounted for another 10.8 billion U.S. dollars (NOAA/National Centers for Environmental Information 2023).

c. U.K. wind drought

Wind droughts are phenomena that are getting increasing attention over the last few years because of their relevance for wind power production. As the number of wind farms continues to rise and expand worldwide, periods of low wind speed become more evident, as recent research has shown that in many regions, the most severe wind droughts occurred before the expansion of wind power made them relevant (Antonini et al. 2023). Related to it, under climate change projections, globally, wind speeds at 10 m are expected to be lower (Deng et al. 2022), although the impacts of climate variability often far outweigh the magnitude of the climate change signal (Bloomfield et al. 2021a), and factors such as multidecadal climate variability or land-use change are as relevant as anthropogenic emissions (Wohland et al. 2021).

One of the problems related to the lack of studies on these phenomena is that there is no consensus definition of a wind drought. For this case study, we focus on an overall decrease in wind speeds, a meteorological variable relevant because of the long period for which it happened and one that was very obvious all along 2021. However, the few existing studies on wind droughts focus primarily on other issues, which may be more significant from the perspective of energy generation such as percentiles of wind power generation, the two curtailment speeds (high and low) that render the turbines inoperative, or the duration of a period with low power generation (e.g., Brown et al. 2021; Liu et al. 2023; Potisomporn et al. 2024).

Some work has been done on energy droughts from renewable sources in the United Kingdom, finding that wind droughts (events with total power production from wind lower than the 10th percentile) affecting the United Kingdom are quite common, with between 6 and 12 events per season, and lasting for 6–11 days (Otero et al. 2022). In summer 2021, a wind drought affected most of Europe, especially the United Kingdom, and the wind speed records in the British Isles were substantially lower than the historical record average (1960–2020). By the beginning of September 2021, wind power accounted for 7% of the electricity production mix in the United Kingdom, to a total of 14% by the end of the year, as compared with 25% in 2020 and 26.8% in 2022 (Mellor 2021; National Grid 2023; Statista 2023).

1) Meteorological context

Wind power production in the United Kingdom has been demonstrated to be strongly related to teleconnection patterns (Brayshaw et al. 2011; Zubiate et al. 2017; van der Wiel et al. 2019; Bloomfield et al. 2020b). During the period in which this wind drought event occurred, the North Atlantic Oscillation (NAO) index (Hurrell et al. 2003) showed mainly negative values, which explains the persistent anticyclonic circulation over the British Isles and the low wind speeds. Figure 4 shows how negative NAO index values are well negatively correlated to low values of wind energy production. During the months where production has been lower (as seen in the graph, July has been the most notable month), the values for the east Atlantic (EA) and Scandinavia (SCAND) teleconnection patterns (Barnston and Livezey 1987) also show high values. From April to September, the correlation of wind power production in Scottish Power farms was a remarkable −0.92 and −0.84 with the SCAND and EA patterns, respectively, and −0.77 with NAO.

2) Consequences

In the United Kingdom, wind power production was considerably reduced for most of 2021, especially from April to September. According to Scottish and Southern Energy (SSE) plc, which operates in the United Kingdom and Ireland, renewable power production (including hydropower) was 32% lower than expected for this period mainly driven by the wind drought (SSE plc 2021). According to Iberdrola/Scottish Power, anomalies in production in their wind farms in July were 43% below the historical monthly average for 1990–2019 (note that the wind speed data reported here were not used to calculate the wind power output), being the second year with lower production of the data series. The U.K. government reported that wind power contributed 14% less in 2021 than in 2020, despite the production capacity rising by 5.3%, due to lower wind speeds (0.6 m s^{-1} below the average) (Department of Business, Energy and Industrial Strategy 2022). As a result, the lack of wind power had to be covered by other sources, including the restart of a coal plant, which resulted in increased CO_2 emissions (Mellor 2021). At the same time, there were problems with the French interconnector, which was offline due to a line failure, so regular nighttime supply from France was not available to support the challenging conditions. It also had an impact on electricity prices, as the demand had to be fulfilled with other fossil fuel sources, which had suffered marked price increases because of the postpandemic increase in demand.

d. Floods in Shanxi

In 2021, there were several EWEs in China. It is estimated that convective weather events alone caused economic losses in the country of 4 billion U.S. dollars (Li et al. 2022). At the beginning of October 2021, record-breaking precipitation and

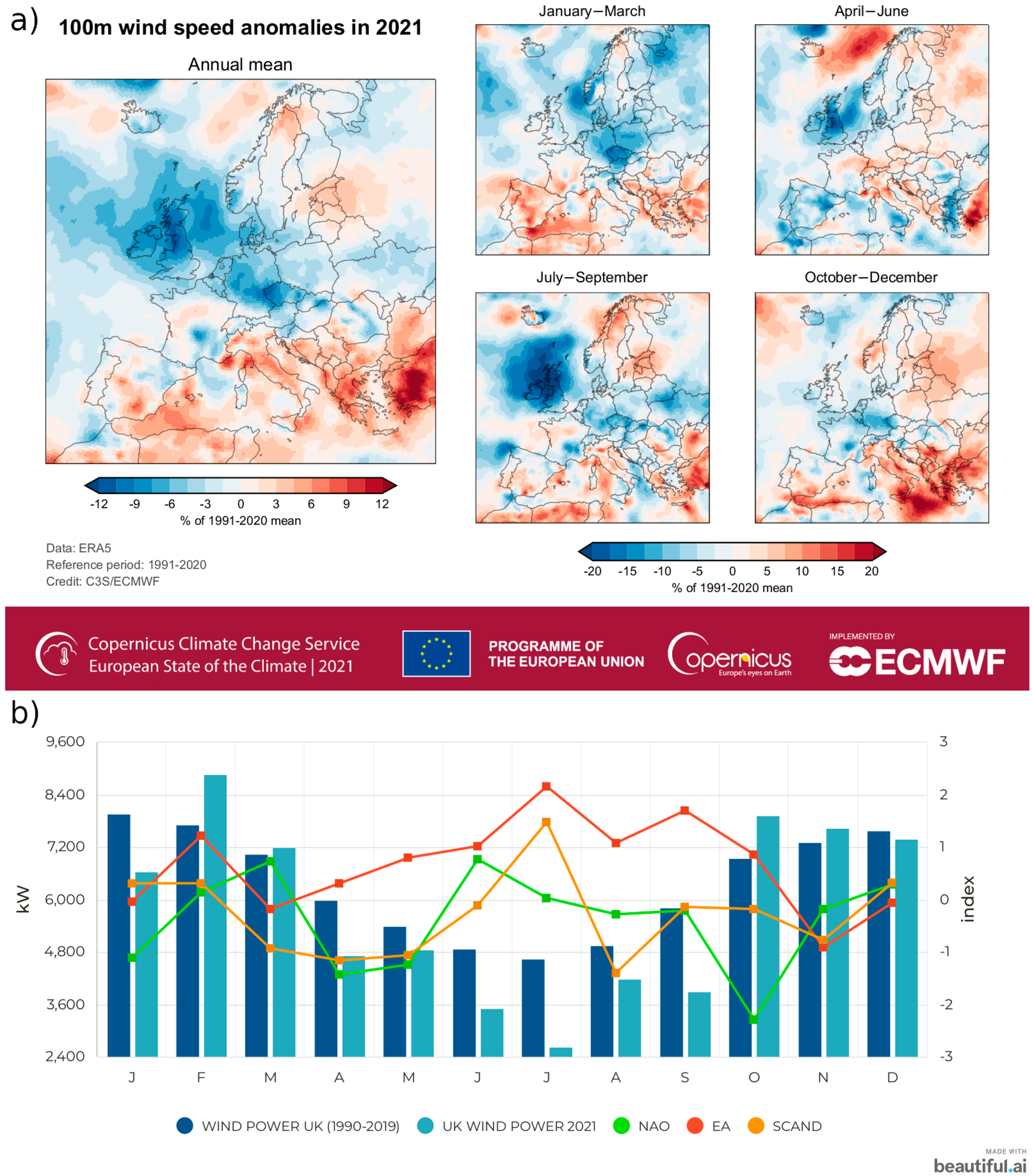

FIG. 4. (a) Wind rankings for 2021 and different seasons over Europe (Source: ECMWF 2022). (b) Average wind power production in Scottish Power wind farms in the United Kingdom for 1990–2019 (navy blue) and wind power production in the United Kingdom in 2021 (light blue). NAO index (green), EA index (red), and SCAND index (orange) in 2021. Data for the indices were obtained from NOAA. Source of wind power production: Iberdrola S.A.

floods happened over northern China, estimated to have return periods of 1 in 1500 years (JBA Risk Management 2021). This extreme rainfall had huge impacts on the energy sector, mainly on coal extraction from mines and energy markets. The region most affected was the province of Shanxi. Over northern China, the rainy season has generally occurred during the summer; however, it has been observed that the usual rainy season in northern China has been extending into the autumn in recent years (Che et al. 2021). There are several different mechanisms causing the timing shift, including, for example, the phase of El Niño–Southern Oscillation and the Indian Ocean dipole (Xu et al. 2016).

During the rainy season (the transition to autumn), climate change projections indicate that there will be an increase in the amount of rainfall exceeding the 95th percentile on a single day. Values of accumulated precipitation over five days, and the number of days with precipitation above 20 mm are expected to increase by 15%–20% by 2039–58 (Qin et al. 2021). Also, recent work focusing on the episode of extreme precipitation for this region the month before this case study has shown that climate change increased their probability twofold (Hu et al. 2023).

1) METEOROLOGICAL CONTEXT

During the first two weeks of October (1–14 October), torrential rains occurred in the Shanxi region (37.0°N, 112.0°E), with the heaviest rainfall happening between 2 and 7 October. The precipitation anomalies were up to 450% above the historical mean (1980–2020) according to ERA5 (see Fig. 5) (other sources report values of 300%; Li et al. 2022). This precipitation came after a September in which it had already exceeded the historical mean in northern China by 300% (Sun et al. 2023), and catchments were saturated and susceptible to flooding.

Synoptically there was a stable situation (it lasted for several days) over Shanxi with low pressures to the west and high pressures to the east (Liu 2022). The western Pacific subtropical high was located abnormally far north, and its west ridge was abnormally far east, in a configuration that favored the transport of warm and humid air to the region. This facilitated the precipitation for an extended period. An emergent La Niña event has been pointed out as an additional contributing factor (Che et al. 2021; Gu et al. 2022). The rainfall recorded between the evening of 2 October and the morning of 7 October was 119.5 mm, exceeding historical maximums (Zhou et al. 2022). According to JBA Risk Management (2021), in Taiyuan, the capital of the Shanxi region, cumulative precipitation of 185.5 mm was recorded in 12 h. This is more than triple the historical maximum recorded between 1979 and 2021 and more than 7 times the average October rainfall of 25 mm observed between 1981 and 2010. In Daning County, southwest of Shanxi, a cumulative precipitation of 285.2 mm was recorded in 12 h, breaking the seasonal record by 7 times. During this episode, many meteorological stations in the region recorded historical maximums of precipitation. The precipitation recorded in Shanxi in five days was more than triple the average monthly rainfall for October. The rainfall on 2 October caused the Fen River in Taiyuan to reach a maximum water flow of 1100 $m^3\ s^{-1}$, which is more than 20 times its usual rate and the highest since 1996. Because of this, several levees were breached, causing severe flooding in Yuncheng in southwestern Shanxi, near the confluence of the Fen He and Huang He rivers (Feng et al. 2022).

2) CONSEQUENCES

With more than 600 coal mines in the region, 30% of the coal extracted in China comes from Shanxi. Because of the

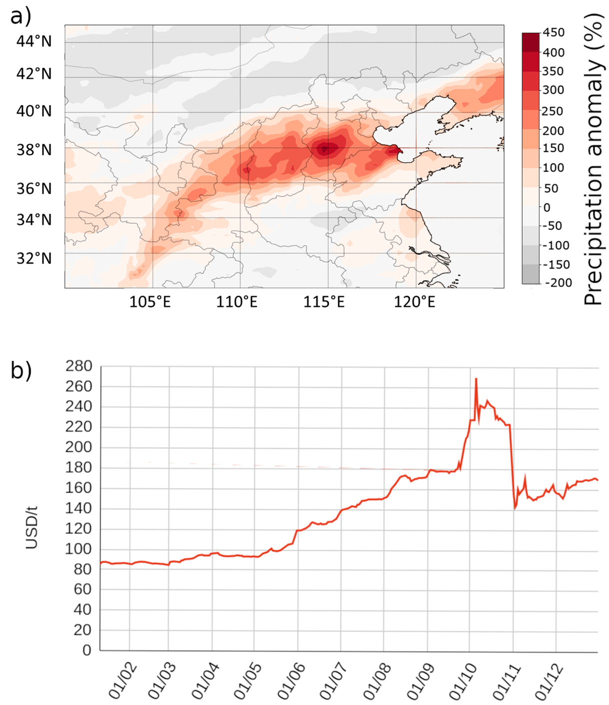

FIG. 5. (a) Anomaly of precipitation for the Shanxi region for October 2021 relative to the historical mean (1980–2020) for the same month. Data source: ERA5 total precipitation hourly data. (b) Evolution of spot coal price in 2021 in U.S. dollars per metric ton.

floods, approximately 10% had to stop operating, heavily stressing the supply chain in a preexisting context of energy peak prices because of the industrial recovery after the COVID-19 pandemic (International Energy Agency 2021a). Given the significant percentage that coal thermal power contributes to the electricity mix in China (almost 55% in 2021; Ritchie et al. 2022), as a consequence of the lack of coal, authorities had to implement electricity outages in 20 of the 31 regions of China. Also, the coal market registered record prices because of global demand, peaking at \$269.5 t^{-1} on 5 October (see Fig. 5).

On 15 October, the situation worsened because of increased demand associated with an episode of low temperatures in most of China, with thermal power plants rushing to stock up on coal. In response to the situation, the Council of State requested mines increase their production, letting them surpass the maximum annual allowances. As a consequence, inflation rose by 0.91%, leading to a 1% rise in the producer price index and a rise of 0.5% in the consumer price index (Tianfeng Securities Co. 2021; Bloomberg News 2021), the total cost of the Shanxi floods is estimated to be between 770 and 707 million U.S. dollars (Lalzoy 2021; Zhou et al. 2022).

4. Discussion

EWEs pose a substantial risk to the energy sector, and climate change is increasing the number and risk of these events. Therefore, preparedness and adaptation are necessary. Here, we have reviewed some of the more relevant cases in 2021, showing that such events can be diverse and triggered by a range of different meteorological drivers. Some of the events show how seasonal and subseasonal forecasting represents an opportunity to prevent and mitigate their impacts, which has been extensively pointed out in previous research (e.g., Troccoli et al. 2014; Añel 2015; Orlov et al. 2020; Bloomfield et al. 2021b; Bayo-Besteiro et al. 2022; Domeisen et al. 2022). Some others show how a better knowledge of the stratosphere and its coupling with the troposphere plays a role (Añel 2016). The fingerprint of La Niña is present in three of the EWEs studied, and other teleconnection patterns, such as NAM and the MJO, are linked to others. Previous research on the "Beast from the East" has already shown how the electricity demand in Europe can be driven by these and other teleconnection patterns, jointly with the phenomenon of polar vortex weakening and the associated excursion of polar air masses in midlatitudes (Beerli and Grams 2019; Bloomfield et al. 2020a). This is similar to what happened for winter storm Uri. Also, it is obvious that climate change has a role in EWEs; however, for many of the cases presented here, the relationship has been studied, and it is obvious, but for others it is not so clear. There are even cases that could become less frequent, such as Filomena (Faranda et al. 2022).

The case studies presented here were quite prominent in a year that featured an energy market struggling with generation and energy prices in a postpandemic scenario with economic recovery and in a year with several relevant meteorological and climatic features such as droughts, heat waves, floods, wildfires, winter storms, a major SSW, and La Niña. However, one of the main problems when reviewing the impacts of extreme weather on power systems is in finding information on case studies from some regions. The lack of cases for which we have found information for the Global South is readily apparent and in stark contrast to the comprehensive literature available about the winter storm Uri. Forensic analysis of these events, both from the meteorological and technical sides, is necessary for good future planning, even more so under climate change, and no doubt beneficial for any region and operator, not only those involved in the case studies. In this way, more openness in data and reports regarding the impacts of weather on the energy sector is desirable from stakeholders and researchers in other regions less studied.

Other conclusions from this work are that despite existing warnings and research results, stakeholders' efforts in adaptation can be clearly improved. In this regard, there are two aspects of grid resilience: meeting the electricity demand and ensuring that the infrastructure to deliver electricity is resilient to EWEs.

For the first aspect (meeting electricity demand), work published more than 15 years ago had already pointed out how heat waves under climate change can drive problems in the power supply in California because of excess demand (Miller et al. 2008). Diversification in power generation sources, adoption of renewable sources and improvements in interconnection in the electricity grid can increase resilience to EWEs and climate change. For example, during Filomena, the Spanish electricity generation and transmission system (with a substantial percentage of generation capacity in renewable sources) coped well with both generation and demand. However, the high reliance of Texas on thermal power plants and fossil fuels, with coal, nuclear, and gas accounting for almost 75% of the generation, and only 25% additional from wind power (solar and hydropower generation is minimal) (DOE 2021) has been pointed out as one of the weaknesses that lead to the disastrous impact of Uri (Popik and Humphreys 2021). Additionally, it has been demonstrated that technologies such as photovoltaic power are resilient to climate change, which is unlikely to threaten their production (e.g., Jerez et al. 2015; Bayo-Besteiro et al. 2022). Also, other technological solutions, such as using storage systems (e.g., batteries for short periods of time or reverse hydropumping reservoirs for long-term storage), could help alleviate phenomena such as renewable energy droughts (Rinaldi et al. 2021).

For the infrastructure aspect, recommendations for weatherization and preparedness to EWEs in Texas had been made by the U.S. Federal Energy Regulatory Commission (FERC) based on up to three previous EWEs, including an excursion of polar air masses similar to part of the Uri storm (FERC 2021). Also, the adaptation of the generation systems, transmission lines and the market managed by ERCOT in Texas did not consider extreme weather or possibilities for peak demand during winter (Popik and Humphreys 2021), and this played a key role in the disaster caused by the Uri storm. In this vein, although very different in nature, the comparison between the impacts of Filomena and Uri shows how the investment and preparation of the power generation system and interconnection of transmission lines can be key to improving the resilience of the energy system against EWEs. The economic viability of the winterization of systems to avoid cases produced by episodes such as the Uri winter storm has been studied (Gruber et al. 2022), showing that the social cost of inaction is tenfold the cost of adaptation. Increasing the use of forecasts on potential weather risks for the energy sector would be beneficial for adaptation. For example, the 2023 summer forecast of the North American Electric Reliability Corporation reports on the potential impacts of heat waves and wildfires across the United States (Scharping 2023). However, even if the issues caused by EWEs are acknowledged, adaptation can still be a lengthy process. EWEs and climate change have begun to be incorporated into official energy system planning by utilities and governmental entities only in recent years, and it is a work in progress. Also, stranded assets play an important role in the energy sector, where investments in power generation plants and technologies need years to pay off, and building new generation facilities can be somewhat slow because of politics or local opposition. In this regard, adaptation and preparation of the energy sector for EWEs and climate change will benefit politics, favoring the deployment of renewable energy installations.

In recent years, actions have begun to be carried out to adapt the energy sector to climate change and EWEs. The European Climate Adaptation Platform and the European Union policy include energy security through renewables as a key point (Climate-Adapt 2023). The International Atomic Energy Agency published a review in 2019 on adaptation to climate change, discussing the role of EWEs (International Atomic Energy Agency 2019). Also, the U.K. Third National Adaptation Programme (Department for Environment, Food and Rural Affairs 2023) published in July 2023 specifies the mandate "to build climate and weather resilience" in the energy sector, and establishes floods, lack of water availability, and extreme temperatures as the main risks for energy security. Specific actions to adapt to these key risks are provided and some of them are needed in the very short term. The focus on floods as one of the main risks for the energy sector over the coming years coincides with the direction and worries exposed by the International Energy Agency (Lim 2023). Additionally, recent actions to provide helpful climate services with the engagement of stakeholders have been deployed. These are an excellent way to adapt the energy sector against EWEs and climate change according to its needs (Goodess et al. 2019).

Many lessons have been learned from the cases reviewed in this paper and the actions to avoid them happening again. Preparedness against floods and an increase in the share of renewable energy in the mix are two of the main measures being deployed worldwide. Some cases have undergone "forensic" analysis, and measures have been proposed. For example, after the Uri storm, the city of Austin and Travis County requested a report (City of Austin Homeland Security and Emergency Management 2021); however, it focused on the emergency response. The references to the measurements regarding the disruptions in the grid are only from the side of the causes of disruption, and the recommendations are limited to increasing the existence of in situ backup power generators that do not depend on external electricity sources. On the other hand, California publishes its climate adaptation strategy every three years, the last one in 2021; In April 2022, after the heat wave the previous year and public consultation in 2021, it released a separate extreme heat action plan (California Natural Resources Agency 2022). This plan contains a wide number of actions for the energy sector, such as continuing to include extreme heat and its impacts on energy demand into Integrated Energy Policy Report forecasts, to protect energy systems from the impacts of extreme heat and increase energy resilience during extreme heat events through improvements for grid reliability (some of which were already completed by the publication of the plan) and to increase "reserve margin" power resources. It also includes a goal to develop enhanced demand forecasts that consider the likelihood of EWEs.

Note also that the energy sector is one of the most vulnerable to risks derived from compound EWEs (Niggli et al. 2022) and that EWEs with energy sector impacts can also impact human lives and can exacerbate social inequalities (Nejat et al. 2022; Zanocco et al. 2022). At the same time, improved EWE warning systems can help reduce CO_2 emissions through a more efficient and safe use of energy. These are some of the reasons to devote efforts to studying EWEs and investing in increasing the resilience of the energy sector to them.

This study elucidates the impact of meteorology on society through the lens of EWEs and their influence on the energy sector. We delve into the varied consequences of distinct events that unfolded in 2021, framing them within their meteorological context. A specific focus is the inclusion of phenomena such as wind droughts, an area that is relatively unexplored and emerging. Moreover, results are based on exclusive data from a private wind energy company, offering insights that are typically not readily accessible. Overall, this paper provides a comprehensive overview of the pivotal meteorological events of the year 2021 and their implications for the energy sector.

This study underscores the crucial role of weather forecasting in society, particularly within the energy sector. By considering potential risks, the adaptation and resilience of energy production and transmission systems are enhanced. These aspects not only present an opportunity to optimize the economic aspects of the energy system but also help in averting potential damage mitigation costs. Additionally, they provide a foundation for making informed political decisions geared toward system optimization. The tangible manifestation of this issue is observed on a global scale year after year. A notable instance is the 2023 floods in Libya (Nagraj and Benny 2023), a country heavily reliant on hydrocarbons for energy. Such extreme phenomena resulted in a significant spike in oil prices, showcasing the real-world implications of weather-related challenges. Events like fires have far-reaching impacts, evident in the 180 million U.S. dollars losses incurred in the photovoltaic solar energy sector in the United States between January and March 2021. Such incidents underscore the need for robust fire prevention and extinguishing policies in areas lacking current measures. In the Indian context, Dumka et al. (2022) exemplify how Earth observation data, coupled with passive and active remote sensing techniques and model simulations, offers a realistic representation of atmospheric effects on solar energy production during fire periods. The phenomenon of a wind drought, or periods of stillness, demands dedicated study due to its adverse effects on the energy sector, particularly in reducing wind production. This issue is gaining prominence globally, as the International Energy Agency highlighted in its *2023 Energy Efficiency Report* (International Energy Agency 2023). The report emphasizes the global relevance of weather-related challenges, exploring their implications and associated risks, especially in situations of exceptional warmth linked to surges in demand and the ensuing risks within the energy sector.

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S.A. and cannot be redistributed. The coal carbon prices were obtained online (https://tradingeconomics.com/) and cannot be redistributed.

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