Sustainable Energy Technologies and Assessments 62 (2024) 103607

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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

The impact of extreme dust storms on the national photovoltaic energy supply

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ARTICLE INFO

Keywords:
Photovoltaics
Dust storm
Power generation mix
Soiling
Spain

ABSTRACT

This study analyses the consequences of an extreme dust storm that occurred in March 2022 on the Spanish national photovoltaic (PV) energy supply. This event, indeed, substantially raised the particulate matter concentrations and the aerosol optical depths across the country, seriously affecting the surface radiation and posing a substantial threat not only to individual PV systems but also to the national electricity grid. The research, based on the analysis and the forecast of weather, environmental and electrical data, reveals that such event halved the capacity factor of the national PV fleet over a period longer than two weeks. A peak drop as high as 80% was registered, at national level, on the worst day. This underperformance also affected the market share of PV in the national electricity mix, whose monthly average value fell from the predicted 10.9% to 7.1%. Despite the expectations, however, no significant difference in soiling was found compared to the typical losses, thanks to the occurrence of heavier-than-usual rainfall events. This facilitated the recovery of the national PV capacity, which returned to the expected performance factors as soon as the sky cleared.

Introduction

Solar photovoltaics (PV) is the fastest growing energy technology worldwide [1]. In just a decade, its cost has dropped by almost 90 %, making it cheaper than fossil fuels and cost-competitive with wind energy [2]. This has led to unprecedented deployment rates [3], which will make PV the most installed energy technology worldwide by 2027 [4]. As the capacity raises, also the penetration of PV in the national electricity markets becomes higher. This means that the national electricity demands are growingly relying on this technology. Therefore, any disruption on the PV performance can have severe local, regional and national repercussions, potentially affecting the reliability of the national energy systems and posing risks to grid's power quality, reliability, and stability [5].

In 2022, Spain became the largest PV market in Europe and the seventh worldwide [1]. According to the data of the national grid operator (REE) [6], the Spanish peninsular grid-connected PV capacity increased by 432 % and 230 % since the start of 2019 and 2020, respectively, reaching 19.8 GW_{AC} at the end 2022. Of these, 4.5 GW_{AC} were installed just in 2022, 22 % of the total capacity, and 17 % more than in the previous year. At the end of June 2023, the capacity had already reached 21.9 GW_{AC}. Thanks to this impressive growth, PV supplied 11.6 % of the peninsular electricity demand in 2022. This percentage had already risen to 16.0 % in the first six months of 2023 (vs 11.5 % in the same period of 2022).

PV modules convert the incoming irradiance into electricity. The intensity of the irradiance, along with its spectral profile, is however affected by both the apparent position of the Sun and by the weather conditions. Clouds, aerosols, water vapor and ozone can, indeed, absorb, reflect and deflect part of the sunlight, reducing the intensity of the irradiance reaching the PV modules. This means that the PV performance is likely to worsen when dust and sand storms occur. During these events, indeed, large amounts of dust and sand are suspended [7], reducing the intensity of the radiation that reaches the Earth's surface. From the analysis of climatology data spanning from 2003 to 2017, Papachristopoulou et al. [8] found that dust storms could reduce the global horizontal irradiance (GHI) and the direct normal irradiance (DNI) over Southern Spain by up to 5 % and 23 %, respectively. Similarly, they also estimated potential reductions of up to 4 % in GHI and 19 % in DNI over the rest of Europe. Kosmopoulos et al. [9] analysed the

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https://doi.org/10.1016/j.seta.2024.103607
Received 13 October 2023; Received in revised form 4 December 2023; Accepted 3 January 2024
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effects of a dust storm in early 2015 on the eastern Mediterranean region and found that such extreme events could reduce the GHI by up to 50 % and the DNI by up to 90 %. In particular, they reported slightly higher losses in the ultraviolet waveband compared to visible and infrared regions. Chaichan et al. [10] measured a drop in radiation by almost 55 % during an event in Baghdad, Iraq, compared to the previous clear day. During a three-day dust storm in India, Masoom et al. [11] found drops of 10 % and 40 % in global horizontal and direct normal irradiance, respectively. Monteiro et al. [12] found that during a dust storm in Greece, the GHI dropped by 20 % and the DNI by more than 50 %, leading to a drop in PV performance that caused the loss of € 8.6 k/MW.

However, in addition to the concurrent effect of suspended particles, dust storms can have longer-lasting consequences. Indeed, the suspended dust particles can deposit on the PV modules, leading to soiling losses and prolonging the consequences of the dust storm even after the sky has cleared. Adinkoyi et al. [13] reported that the soiling accumulated after dust storms in the eastern part of Saudi Arabia could lead to power drops of 20 %. Conceição et al. [14] found that the dust deposited after events occurred in Portugal in February and March 2017 induced losses up to 7 % and 3 % respectively. Khodakaram-Tafti and Yaghoubi [15] reported reductions in daily energy generation ranging from 20 % to almost 60 % for PV modules mounted at different tilt angles in Iran. Javed et al. [16] reported that soiling, during dust storms, can accumulate at rates up to 2.41 %/day in Doha, Qatar.

Locations with higher solar potential are more likely exposed to the effects of dust due to their more arid/desert environments or their proximity to them, and to the typically lower probability of cloud cover (Fig. 1). Europe is particularly exposed to dust storms, as the Mediterranean area includes some of the regions with higher dust risks, such as north Africa and the middle East [17]. Indeed, the Sahara is the largest source of atmospheric desert dust, followed by the deserts in China, Central Asia, Saudi Arabia and Australia [18]. Even if dust storms are predominant in the arid and semi-arid regions where they originate, several Saharan dust intrusions have been reported over different north American and European countries in the past years. For example, as also mentioned earlier, Saharan dust storms and associated health hazards were reported in Mexico in 2017 and 2018 [19], in Greece in 2015 and in 2018 [9,20], in Republic of Moldova [21], in the Caribbean Basin and in the southern U.S. in 2020 [22], in the United Kingdom in 2019 [23], in 2022 [24] and in 2023 [25] and recently in Spain, Italy and Southern France [26]. This means that, while the number of PV installations grows, the resilience and reliability of national grids might be put increasingly at risk by the impact that dust storms can have on the national PV capacity. In this light, this work investigates two dust storms that occurred in Europe during the second half of March 2022 [27]. In particular, it focuses on the consequences that these events had on the Spanish photovoltaic sector and, subsequently, on the national electricity grid.

The motivation behind this work relies on the possible effects of dust storms, whether of ordinary or extreme magnitude, on the electricity grids. According to a study by Clifford et al. [30], Saharan dust events are becoming less frequent but more intense. However, a statistical analysis conducted by Salvador et al. [31] found an increase in both the frequency and intensity of Saharan dust intrusions over the Western Mediterranean basins from 1948 to 2020. Regardless of the long-term pattern, Europe was affected by several intense Saharan dust intrusions during the 2020–2022 winters, at a significantly higher frequency than in the same seasons of the 2007 to 2019 period [32]. Understanding the effects of such events is therefore mandatory, especially in Western Europe, given its exposure to Saharan dust intrusions and the ambitious PV capacity goals [33]. To ensure a continuous and reliable power supply, it is imperative that the electricity infrastructure and grids can withstand both ordinary and extraordinary dust events and can effectively mitigate their impacts on power provision stability.

So far, the literature has been focused on the effects of dust storms on a single location or PV system. However, one should take into account that these events can affect large areas and, therefore, a significant number of PV power plants. This means that, given the increasing penetration of PV in the national electricity grids, dust storms can have also macro-scale effects, which have not been investigated in detail so far. For example, dust storms can force prolonged changes in the electricity mixes because of the sudden and potentially protracted drop of solar resource. In some cases, the missed solar electricity might have to be replaced by fossil fuel-based technologies. This can have consequences on both the grid emissions and the electricity prices. Therefore, in light of the ongoing renewable energy shift and massive global PV deployment, dust storms can represent a threat for the resilience and the reliability of electricity grids.

Because of the above-mentioned reasons, the present work focuses on the macro-scale effects of the dust storms occurred in Spain in March 2022. In particular, this work investigates the effects that these events had on the national photovoltaic fleet and, consequently, on the Spanish electricity grid. The analysis is conducted by using actual power data shared by the electricity grid operator. The impact of the dust is analysed through the use of clear-sky and actual satellite-derived irradiance data and the results are corroborated from the analysis of aerosol optical depths (AOD), dust optical depths (DOD) and particulate matter concentrations. The findings of the investigation allow, for the first time, to assess the impact of dust storms at national level and are reproduced in two additional countries. Understanding the repercussions of such events can help policy makers and energy players to better design the infrastructure and to identify solutions to improve the reliability of energy systems. In addition, the findings can be considered representative for a number of countries whose weather conditions, geographical position, electricity infrastructure and renewable energy policies are similar to those of Spain. Last, the proposed methodology could be reapplied to different events, which might include additional dust storms, or even wildfires for example [34], to investigate the resilience and the reliability of the national grid of Spain or of other countries in conditions of growing renewable energy penetration.

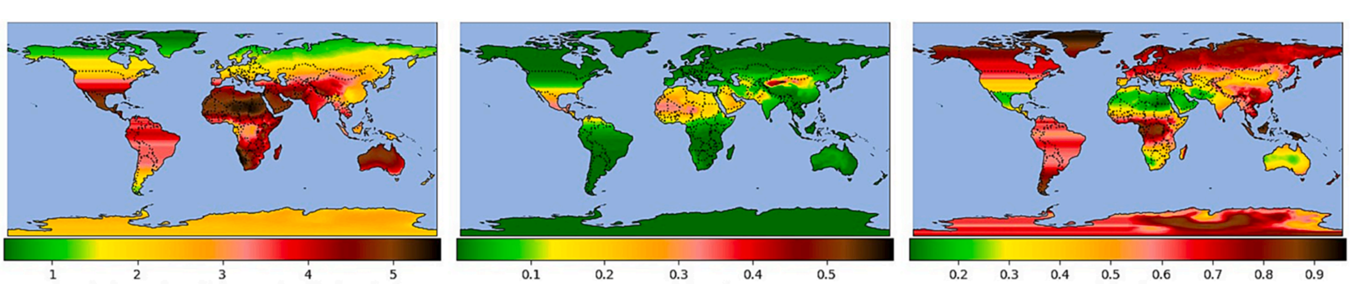

Fig. 1. Maps of average clear-sky direct solar radiation (left), dust optical depth (middle) and total cloud cover (right). The average clear-sky direct solar radiation and total cloud cover values have been calculated from monthly data spanning from 1940 to October 2023, downloaded from ERA5 through the Copernicus Atmosphere Monitoring Service (CAMS) Climate Data Store (CDS) [28]. The average dust optical depth values at 550 nm have been calculated from monthly data spanning from 2003 to 2022, downloaded from the EAC4 (ECMWF Atmospheric Composition Reanalysis 4) of the CAMS Atmosphere Data Store (ADS) [29].

Methodology

The present work focuses on two dust events that occurred in the second half of March 2022 over Europe and specifically over the Iberian Peninsula. The investigated dust storm events, in particular, lasted from March 13 to March 30, 2022. In order to quantify the individual impact of each storm, in some parts of the analysis, the dust storm period is split in two intervals; when the individual events are described, the first interval is considered to last until March 19 included, whereas the second one is set to start from the following day until March 30.

In order to assess the impact of these events on the expected or typical weather conditions and PV performance, multi-year electrical and weather data were downloaded from different sources and analysed. These are described in the following subsections. In particular, the data used for the analysis conducted on the Spanish peninsular grid are presented in the first three subsections. It should be highlighted that, even if occasionally labelled as "national", the data exclusively pertains to peninsular Spain. This means that they exclude information from Canary and Balearic Islands, Ceuta, Melilla, and the Spanish territories off the coast of Morocco. In the fourth subsection, the data used to reproduce the analysis in two additional countries are described. In the last subsection, a discussion on the uncertainty of the results is presented.

Electrical data

Power generation, demand and AC capacity data for the Spanish peninsular grid have been downloaded from the REE website [6] for the period in between January 2015 and September 2023. The national power generation data are available at daily intervals and include a breakdown of the energy delivered by the various sources available in the country. The demand data have been also downloaded at daily intervals. The national capacity of each technology is on the other hand available on a monthly basis and has been converted in daily values using linear interpolation. It should be noted that the data refer to grid-connected utility-scale power plants only.

Spain is divided in seventeen "autonomous communities". Fifteen of these are located in the Iberian Peninsula. The specific data of power generation, technology capacity and electricity demand for each of these fifteen autonomous communities have been also downloaded and analysed. These are available at monthly resolution for the period in between 2015 and 2023.

The aforementioned data have been used to estimate the capacity factor and the market share of photovoltaics in Spain and in each of the communities. The capacity factor is a commonly used parameter to compare the performance of energy technologies. It expresses the ratio of the energy produced to the maximum possible energy output. In this work, the capacity factor of the PV capacity has been calculated as in [35]:

$$CF(d) = \frac{NationalDailyPVGeneration(d)}{NationalDailyPVCapacity(d) \bullet 24h} \quad (1)$$

As aforementioned, both the national daily PV generation and the national daily PV capacity employed in Eq. (1) were downloaded from the REE website [6]. The same equation has been adapted to calculate the mean monthly capacity factor of the individual communities, using monthly generation and capacity data.

On the other hand, the "market share" of a technology in the national grid represents the percentage of electricity demand it provided in a given day. It has been calculated as in [35]:

$$MS(d) = \frac{NationalDailyPVGeneration(d)}{NationalDailyDemand(d)} \quad (2)$$

Also in the case of Eq. (2), both the national daily PV generation and the national daily PV demand were downloaded from the REE website [6]. An analogous equation was used to calculate the monthly market share in each autonomous community.

It should be noted that the first curtailment in Spain took place on April 17, 2022, a few weeks after the investigated dust events occurred [36]. For this reason, curtailment has no effect on the present analysis, as the results focus on the PV and energy market performance in March 2022 and before.

Weather data

Daily solar radiation time series from 2013 to the end of August 2023 were downloaded from the Copernicus Atmosphere Monitoring Service (CAMS) [37] for a 0.5° × 0.5° grid of locations. These are available as both actual weather and clear-sky data [38,39]. The latter ones represent the potential irradiation in cloud-free conditions, but still affected by aerosol, ozone and water vapor. The database contains information on all the components of the sunlight: global, direct and diffuse on the horizontal plane as well as direct at normal incidence.

The most common indices to express the concentration of aerosols at ground level are the PM_{10} and $PM_{2.5}$. These measure the concentrations of suspended solid or liquid particles which are less than 10 μm and less than 2.5 μm in diameter, respectively. These data are typically monitored for health-related reason but have also been commonly used in PV studies. In particular, they have been extensively employed for soiling loss estimation purposes [40–42], as later described. However, they could also provide information on the impact of the atmosphere on the irradiance, as a high concentration of suspended particles is expected to lower the direct component of the radiation. For this work, daily ground-measured PM_{10} and $PM_{2.5}$ data from 2018 to 2023 were downloaded from the website of the European Environment Agency [43]. A total of 273 and 146 monitors recorded at least one daily measurement of PM_{10} and $PM_{2.5}$, respectively, during the investigated period (March 14 to March 30, 2022). Only data from these monitors have been considered in the analysis.

The available ground-monitors are unevenly distributed across the Spanish territory and are mainly concentrated in urban areas. For this reason, PM_{10} and $PM_{2.5}$ concentrations have been obtained also from a satellite-derived database. These data are known to be less accurate than ground-measured ones [44]; however, they are available over a uniform grid of locations and are obtained using consistent methodologies. For these reasons, satellite-derived particulate matter data have been employed to analyse the PV soiling accumulation, as described in the following subsection, and to generate the surface map reported in the "Results and Discussion" section. They have been downloaded at intervals of 3 h from 2018 to 2022, from the EAC4 (ECMWF Atmospheric Composition Reanalysis 4) of the Copernicus Atmosphere Monitoring Service (CAMS) Atmosphere Data Store (ADS) [29].

It is important to recognize that particulate matter values can offer only a partial overview of the dust load. PM_{10} and $PM_{2.5}$ sensors, indeed, represent mostly the lower part of the atmospheric column, whereas a different parameter, i.e. the Aerosol Optical Depth (AOD), is representative for the whole column [45]. For this reason, also daily AOD values at 550 nm were downloaded from 2018 to 2022 at 3 h intervals from CAMS ADS [29]. This parameter expresses the extinction of the solar radiation at 550 nm due to scattering and absorption. Therefore, it is a parameter that provides information on the effect of the aerosol load on a specific wavelength of the solar radiation. It has been also used to classify the intensity of the dust storm, following the methodology proposed by the Gkikas et al. [45]. In this approach, a day *d* experiences a dust event classified as "extreme" if:

$$AOD(d) > \overline{AOD} + 4 \bullet \sigma_{AOD} \quad (3)$$

where $\overline{AOD}$ and σ_{AOD} are respectively the average value and the standard deviation of the AOD time series downloaded from CAMS ADS [29]. Similarly, an event on a day *d* is classified as "intense" if:

$$\overline{AOD} + 4 \bullet \sigma_{AOD} \geq AOD(d) > \overline{AOD} + 2 \bullet \sigma_{AOD} \quad (4)$$

Nevertheless, it should be acknowledged that evidences of CAMS underestimating the aerosol and dust content over the Mediterranean area have already been shared in the literature [8]. For this reason, also ground-measured AOD values were considered in this work, downloaded from the AERONET (Aerosol Robotic Network) program [46], which has a number of stations across Spain. In particular, cloud-screened and quality-assured data (level 2.0) from a number of stations, whose distribution is shown in the Supplemental Information (Fig. S1), were selected.

As aforementioned, the AOD describes the optical effect of the aerosol load over the atmospheric column. However, dust only partly contributes to this. For this reason, the dust induced proportion of AOD can be expressed through the dust optical depth (DOD) [47]. In order to evaluate this effect, also daily DOD values at 550 nm from 2018 to 2022 were download at 3 h intervals from CAMS ADS [29]. The contribution of DOD to AOD can be estimated by calculating the DOD-to-AOD ratio [47]. In order to solely take into account the effect of dust in dust storm classification, Papachristopoulou et al. [8] adapted Eq. (3) as follows:

$$DOD(d) > \overline{DOD} + 4 \bullet \sigma_{DOD} \quad (5)$$

Last, hourly total precipitation and total cloud cover data for the years in between 2018 and 2022 were downloaded from ERA5 through the CAMS Climate Data Store (CDS) [28]. The first variable describes the accumulated liquid and frozen water reaching the Earth's surface. The second one is a parameter that describes the fraction of the sky covered by visible clouds and varies from 0 (no clouds) to 1 (overcast).

Soiling estimation

Soiling consists of the accumulation of dust particles and other contaminants on the surface of PV modules. In presence of soiling, only part of the irradiance hitting the modules reaches the PV material. Therefore, PV modules convert a lower amount of solar energy into electricity. As described by Ilse et al. [48], soiling is the result of three phenomena: deposition, rebound and resuspension. Deposition is the rate at which particles impact the surface; rebound is the rate at which particles bounce off from a surface without adhering, while resuspension is the rate at which particles bounce off after an initial adhesion. The accumulated soiling is therefore the difference between deposition and the sum of rebound and resuspension.

The intensity of these three phenomena depends on weather, pollution and PV site characteristics. The severity of soiling can be expected to increase in presence of dust storms, because of the higher concentrations of aerosols in the air. The correlations between the dust accumulation processes, the environmental conditions and the site characteristics have been modelled by various experts, which have proposed methods to indirectly estimate the PV soiling losses from these parameters [49]. These methods include models based on linear regression, on semi-physical equations, and on artificial neural networks (ANN) [49]. The semi-physical models attempt to reproduce the non-necessarily linear relations occurring during soiling accumulation and have been so far the most commonly employed approach. Indeed, while ANN and most of the other soiling models have been developed and validated against individual sites [50–52], the semi-physical model proposed by Coello and Boyle [53] was validated against data from nine PV sites. This approach has become so familiar to the PV community to be recently included also in pvlib [54], the most well-known Python package for PV performance modelling. For these reasons, it has also been employed in the present work.

Proposed in 2019, the Coello and Boyle model [53] starts from the calculation of the mass accumulation for a given day *d*:

$$m(d) = (v_{10-2.5} \bullet PM_{10-2.5}(d) + v_{2.5} \bullet PM_{2.5}(d)) \bullet t \bullet \cos(\theta) \quad (6)$$

where $v_{10-2.5}$ and $v_{2.5}$ are the static deposition velocities (determined according to the methodology described below), t is the factor used to convert the variables from a one-second interval into a daily value, and θ is the tilt angle, set to 30° in this work. The subscript 10–2.5 indicates that only particles with diameters within 10 μm and 2.5 μm are considered. The $PM_{10-2.5}$ can therefore be calculated as the difference between the PM_{10} and $PM_{2.5}$ concentrations downloaded from CAMS ADS [29].

The daily mass accumulation (*m*) is then converted into a cumulative mass accumulation (*w*), which is reset to 0 on days in which the precipitation intensity is higher than a given threshold. In this work, this cleaning threshold was set to 1 mm/day, as in the original publication by Coello and Boyle [53] and in line with the evidence reported in literature [55].

Last, the daily soiling loss, expressed in %, is calculated as:

$$SL(d) = 34.37 \bullet \mathrm{erf}(0.17 \bullet w(d)^{0.8473}) \quad (7)$$

Given the variability that the sources of the input parameters can introduce in the estimation, the present model was calibrated using actual soiling data collected in Jaén, a town in southern Spain. In particular, a fitting procedure was conducted to determine the static deposition velocities that minimized the deviation between modelled and actual data. The daily soiling loss employed for the recalibration was measured from March 2019 to December 2022 using an Atonometrics soiling station installed in the campus of the University of Jaén. This device is composed of a full-size module that soils naturally and a reference cell that is daily cleaned through a pressurized water spray. The soiling loss can be calculated by comparing the short-circuit current of the two devices. The calibration returned the minimum error if $v_{10-2.5}$ and $v_{2.5}$ were respectively set equal to 3.9 cm/s and 0.8 cm/s.

Impact on other countries

In addition to quantifying the impact of the dust storm on the Spanish national grid, the present work aims to present a methodology that can be used to evaluate the impact of similar weather events in other occasions and countries. In order to prove the reproducibility of the proposed method, the impact of the March 2022 dust storms on two additional countries (Portugal and Italy) was estimated. To do this, the 2015 to 2023 daily PV generation data and installed capacity values for Portugal were downloaded from the website of Rede Elétrica Nacional (REN) [56], the entity responsible for the security and continuity of the electricity service. In addition, the 2018 to 2023 daily PV generation data and annual installed capacity values for Italy were downloaded from the website of Terna, the Italian transmission system operator [57].

Analysis and uncertainty

The study was implemented in Python 3.8. Univariate forecasts were generated through Facebook Prophet [58], a tool which analyses periodic, non-periodic and irregular changes of a given time-series. It had already been successfully employed in PV related studies, for example for modelling non-linear degradation rates [59] and for the estimation of the consequences of the first COVID-19 lockdown on the Spanish electricity market [35]. In order to provide only results with the highest level of confidence, the forecasts are presented here with an uncertainty interval, which, in this manuscript's plots, is represented by a grey shaded area around the forecast. The width of the uncertainty interval was calculated based on the chosen confidence interval, which will be described shortly.

First, it should be noted that this forecasting approach would have not produced reliable results for the market share. This factor, indeed, describes the percentage of electricity demand supplied by a specific technology (PV, in this case). Therefore, as shown in (2), the market share depends on the PV production and on the electricity demand. The first variable is the result of the capacity factor and of the installed capacity, whereas the second one follows a mostly seasonal pattern unrelated to the previous ones. So, historical market share data cannot be used to estimate future trends, as it is the result of independent variables. In order to overtake this issue, the market share forecasts were produced by using a two-step approach. First, individual forecasts were produced for the capacity factor and for the electricity demand using Facebook Prophet. The capacity factor, multiplied by the actual capacity data, provided information on the expected PV production. This way, the forecasts for PV production and electricity demand could be employed to calculate the market share forecasts, as shown in Eq. (2).

The uncertainty of the estimations presented in this work was assessed by producing forecasts of the electricity demand, PV capacity and PV market share for 2021. The daily actual and forecasted values were compared to calculate the mean absolute percentage error (MAPE), and the mean percentage error (MPE). The first metric expresses the average value of the absolute deviations between the forecasted and the actual data. It has a value of 0 % if all the forecasted data match the actual data points. The MPE, on the other hand, provides information on the bias of the correlation. It has a negative value if the forecast tends to underestimate the actual time series, and positive otherwise. An MPE = 0 % does not necessarily imply an MAPE = 0 %. In addition, also the root-mean-square-error (RMSE) was calculated. Also, in this case, the higher the RMSE, the higher the deviation between the actual and the forecasted data. However, differently from the first two metrics, which provide a relative information (always expressed in %), the RMSE has the same units as the investigated variable. This means that the RMSE can be directly compared with the half-width of the uncertainty interval. Ideally, aiming for the most conservative approach, a RMSE lower than half-width of the uncertainty interval is preferred. This way, deviations larger than the uncertainty intervals can be attributed, with higher confidence, to exceptional events, such as those investigated in this study, rather than to noise.

The results of the uncertainty analysis are shown in Table 1. Because of the high periodicity and the low irregularities, the forecast returns low errors for the daily demand and daily clear sky GHI. On the other hand, the forecast returns higher MAPE and MPE for the daily PV capacity factor. This result, however, is not surprising, concerning or unusual. It is indeed due to the effects that clouds and weather conditions have on the actual irradiance and, therefore, on the actual PV performance. Even when historical daily irradiation data are derived from satellite measurements, their deviation from the actual data can range from 10 to 15 % [60]. Overall, when these data are aggregated in monthly values, errors tend to decrease, proving the ability of Facebook Prophet to successfully estimate the typical trend of this variable.

In addition, it should be noted that the errors in daily PV capacity factor correspond to an average RMSE of 4.1 %. In order to take into account the magnitude of the error, a 95 % confidence interval was used for the calculation of the aforementioned uncertainty interval, in place of the default 80 %. This way, the uncertainty interval for the capacity factor has an average half-width of 7.9 %. This is bigger than the reported RMSE and allows identifying those values that are more likely the results of exceptional events rather than due to the intrinsic uncertainty of the forecasting method. The half widths of the same bands, calculated for the electricity demand and daily clear sky GHI, are also shown in Table 1 and, also in these cases, are consistently bigger than the RMSEs.

Table 1
Errors of the Facebook Prophet forecasts, and half width of the generated uncertainty interval. The errors are calculated as difference between the actual and the forecasted data.

Metric	Daily Electricity Demand	Daily Clear Sky Global Horizontal Irradiance	Daily PV Capacity Factor	Monthly PV Capacity Factor
MAPE	6.3 %	2.5 %	27.2 %	8.5 %
MPE	−5.3 %	0.7 %	5.0 %	−4.4 %
RMSE	48.8 GWh/day	202 Wh/m^2/day	4.1 %	1.7 %
Uncertainty half-width	65.4 GWh/day	303 Wh/m^2/day	7.8 %	7.8 %

Results and discussion

Weather and pollution

The occurrence and the significance of the dust storm events under investigation can be seen from the profile of the clear-sky GHI in the left plot of Fig. 2. As aforementioned, two consecutive events occurred in an approximately two-week-long period. The first, extremely intense, dust intrusion took mainly place in between the 14th and the 17th of March 2022. This is corroborated by the report of the Spanish Meteorological Agency [61], which indicates that, on March 14, 2022, a Saharan dust storm entered the Peninsula from the southeast. Strong winds and heavy rainfalls occurring in the southwest of Spain favoured the development of an intense southward circulation over the Sahara Desert in between March 14 and 15. The instability and the cold front associated to those conditions contributed to lifting the dust to high elevations. The strong air circulation in the upper atmospheric levels then carried it over significant distances. While the stormy winds calmed by March 15, the residual dust dispersion continued until March 16 [61]. The left plot of Fig. 2 also shows that a second, less intense, but more prolonged, event mainly took place from the 22nd to the 30th of the same month. In both cases, the average GHI over the peninsular Spain reached values well below the uncertainty interval.

Over the investigated period, the clear-sky GHI dropped by 6.9 % compared to the expectations. The drop is bigger than the uncertainty interval on March 15 to 18 and then again on March 24 to 29. As can be seen, the average GHI on March 16 was 23.3 % below its expected value, a deviation more than 4 times bigger than the uncertainty interval half-width. During the second event, the maximum drop was lower (10.0 % on March 29), but it lasted for a longer number of days.

The left plot in Fig. 2 shows also that the dust intrusions in March 2022 were not isolated events. Dust storms, indeed, took place also in May and in June 2022 [62,63]. This is not surprising, as, in southern Spain, dust intrusions of different sizes have been recorded on 31 % of the days in the 2001–2016 period [64]. However, neither of these events in 2022 was as intense nor as prolonged as the ones investigated in this work. Indeed, the first storm occurred in May 20 to 22, causing a peak loss in clear sky GHI of 12.4 %. The second one occurred from June 13 to 18 and led to a maximum drop in clear sky GHI of 7.4 %.

The impact of dust storm in March 2022 was not uniform across the country but changed in severity and location during the event. This can be seen in Figs. S2 and S3, in the Supplemental Information, which report respectively the variation in clear-sky radiation and the aerosol and dust optical depths across Spain during the first event, when the clear-sky radiation lowered most significantly. As aforementioned, the greatest losses occurred on March 16, with peaks of 30 % and more in the centre and along the southeastern coast of the Peninsula (right plot in Fig. 2).

The same geographical distribution is registered also for the AOD (left plot of Fig. 3), which reached a national average of 1.07 on March 16, with peaks higher than 1.9 and up to 2.7 in the aforementioned regions. These values are significantly higher than the typical AOD values recorded in the country. From the analysis of the 2018 to 2021 data, indeed, an average AOD of 0.13 ± 0.08 is found for the investigated area. The values registered during the investigated period are also considerably higher than the typical 0.4 threshold used by NOAA to define very hazy days [65]. The average value calculated over the whole investigated period is 0.46 ± 0.21 and is also higher, even if slightly, than this level.

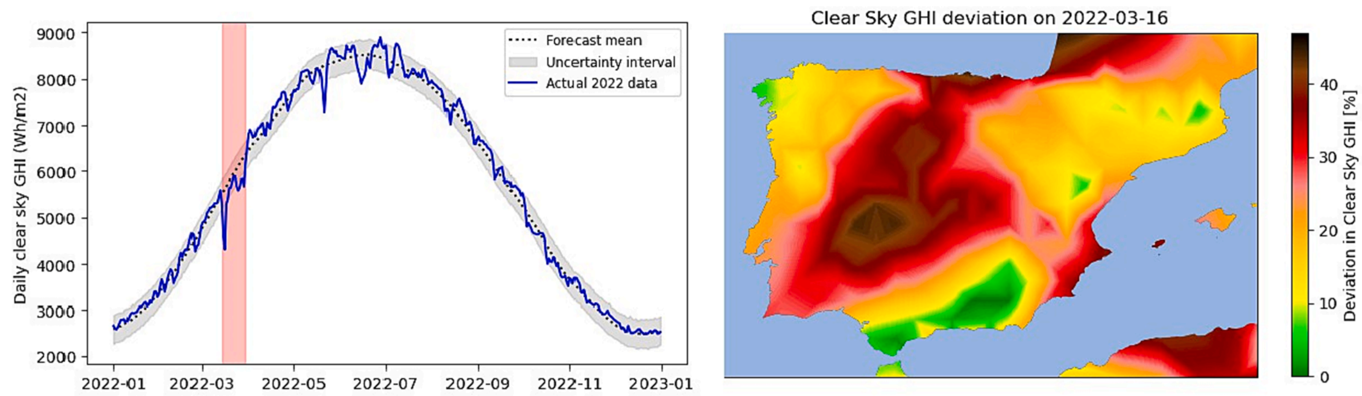

Fig. 2. Left plot: average clear sky global horizontal irradiation in 2022: actual data (blue line) and forecast (dotted black line and grey area). The investigated period is highlighted in red. Right plot: deviation of the daily clear-sky global horizontal irradiance (GHI) on March 16th, 2022. The data are shown as difference between the actual and forecasted GHI value, calculated for the 2022 using the 2013 to 2021 data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

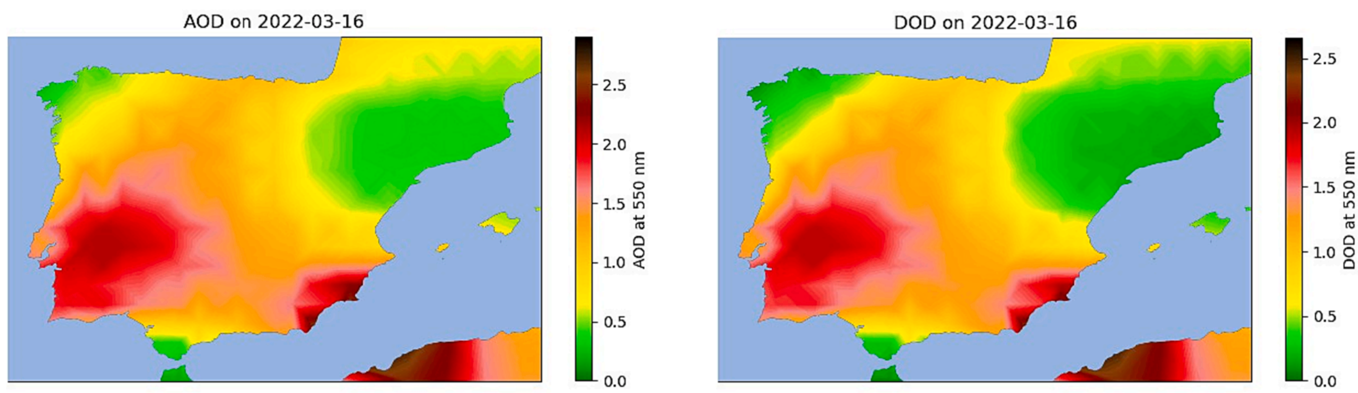

Fig. 3. Left column: aerosol optical depth on March 16th, 2022. Right column: dust optical depth on March 16th, 2022.

Based on the classification proposed by Gkikas et al. [45] and detailed in Eqs. (3) and (4), the investigated dust event is considered “extreme” in over 50 % and 75 % of the peninsular territory of Spain on March 15 and 16, respectively. During these days, between 80 % and 90 % of the territory experienced either an extreme or an intense dust episode. The percentages decreased during the second event, when the storm was classified as at least “intense” over more than 70 % of the land between March 25 and 29. On March 25 and 26, 38 % and 40 % of the locations experienced a dust event of “extreme” intensity.

If the mean AOD value across the peninsula is considered, the dust event is classified as extreme on March 15 to 17, 25, 26 and 29. In the rest of the days of the investigated period, with the exception of March 19, 21, 22 and 23, the dust storm is classified as “intense”.

In order to quantify the impact of such high aforementioned AOD values on the irradiance, a simulation was conducted using SMARTS [66]. This tool simulates the spectral irradiance profiles for a variety of conditions. In this work, it was employed to estimate the drop in GHI caused by an increase in AOD, considering AOD values of 0.084 (default value for reference ASTM G173 spectrum), 0.4 (very hazy day), 1.0 and 2.8 (average and 99th percentile values recorded during the worst day). The remaining parameters are fixed to the default reference values, and the broadband GHI is calculated as average in between 400 and 1100 nm. The results of the analysis show that, compared to the default conditions (AOD = 0.084), AOD values of 0.4, 1.0 and 2.8 cause a drop in broadband GHI of 6 %, 17 % and 45 % respectively. The latter ones, compared to the very hazy day conditions (AOD = 0.4), cause drops of 12 % and 41 %.

Similar results to those registered for the AOD were obtained for the DOD (right plot of Fig. 3), which reached a national average of 0.87 on the worst day, March 16. In this case, a 90th and a 99th percentiles of 1.7 and 2.5 were reached, out of a typical average 0.03 $\pm$ 0.05 DOD registered across the country in between 2018 and 2021. The average DOD-to-AOD ratio during the investigated period was 0.43 $\pm$ 0.18, about four times higher than its typical value (0.11 $\pm$ 0.13). It reached a maximum national average of 0.74 on March 16, with local peaks higher than 0.90. These results further prove the significant contribution of dust to the extreme conditions experienced during the investigated period. In line with the aforementioned results, the methodology proposed by [8] and detailed in Eq. (5) classifies the dust events on March 15 to 17 and 25 to 27 as “extreme”.

The exceptionally high AOD trends provided by CAMS and shown in Fig. 3 are quantitatively confirmed by the measurements available in AERONET (Fig. S1). Among the stations located in Spain, only one recorded data during the first event. This is located in A Coruña, a city in the northwest of Spain (left plot of Fig. S1). In particular, AOD values of 0.5 or lower were recorded until 09:15AM of March 15. Then, they ramped up to 3.0 and 2.9 at 01:29PM and 01:44PM. The following measurements, whose value had already dropped to 0.1, are available from the morning of March 17. No other station has data available for peninsular Spain during the first event. On the other hand, a larger number of stations has data available for the second event (right plot of Fig. S1). During those days, values as high as 0.48 and 0.56 were measured on March 27th and 30th in A Coruña, whereas the additional stations measured peaks around 1.0 in between March 26th and March 29th.

An additional indicator to assess the severity of dust storm events is the concentration of particulate matter in the air, typically expressed through the aforementioned PM_{10} and $PM_{2.5}$. The European air quality standards impose binding annual limits of 40 μg/m^3 and 25 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively [67]. In addition, the maximum PM_{10} concentration of 40 μg/m^3 must not be exceeded on more than 35 days/year. This limit was overtaken by 26 % of the daily measurements taken during the investigated period. In other words, on average, each station measured PM_{10} concentrations > 40 μg/m^3 on 4 days during the second half of March 2022. On March 15, 16, 28 and 29, a percentage in between 69 % and 78 % of the monitors was above this limit.

From the analysis of the ground-measurements, it is found that, during the days of the dust storms, peninsular Spain experienced average concentrations of PM_{10} and $PM_{2.5}$ of 43.1 ± 77.9 μg/m^3 and 15.3 ± 21.6 μg/m^3. On average, in between 2018 and 2023, the same stations measured concentrations of PM_{10} and $PM_{2.5}$ of respectively 20.3 ± 22.5 μg/m^3 and 9.5 ± 7.7 μg/m^3. The storm had therefore a bigger impact on PM_{10} (factor of 2.1 ×) than on $PM_{2.5}$ (1.6 ×). This is not surprising, as previous works have shown that typically the diameter of the particles transported by Saharan dust storms is bigger than 5 μm [68].

Even in this case, the data show a significant difference between the first and the second event. During the first wave, the peaks were reached on March 15, with average PM_{10} and $PM_{2.5}$ concentrations of 192.2 μg/m^3 and 46.6 μg/m^3 respectively. As shown in Fig. 4, on that day, about 5 % of the monitors measured concentrations higher than 590 μg/m^3 and 150 μg/m^3, with maximums in the order of 1700 μg/m^3 and 700 μg/m^3 registered by a monitor in the province of Almeria, in the southern Andalucía community. Lower concentrations were instead found for the second event. The daily maximums of 51.6 μg/m^3 and 19.7 μg/m^3 were achieved on March 29, and no monitor measured more than 99 μg/m^3 and 33 μg/m^3.

Fig. S4, in the Supplemental Information, shows the evolution of the PM_{10} and $PM_{2.5}$ concentrations measured by the ground-sensors installed in Spain during the first event. The highest particulate matter concentrations during the days of the first storm are found in those regions located in or nearby the centre of the Peninsula or the south-east: the communities of Andalucía (76.7 μg/m^3 of PM_{10} and 23.2 μg/m^3 of $PM_{2.5}$), Región de Murcia (66.1 and 22.0 μg/m^3), Castilla y León (54.8 and 16.1 μg/m^3), and Castilla la Mancha (54.1 and 15.1 μg/m^3). This result is particularly significant as these four communities hosted, in March 2022, 58 % of the national PV capacity.

The same results are confirmed from the analysis of the satellite-derived data. Indeed, average concentrations of PM_{10} and $PM_{2.5}$ of 64.4 ± 21.1 μg/m^3 and 46.0 ± 14.9 μg/m^3 are found. Also according to this dataset, these values are significantly higher than the typical ones, 15.3 ± 7.3 μg/m^3 and 10.4 ± 5.5 μg/m^3, even if by larger factors. As can be seen, however, even if the two data sources return the same trends and confirm the findings of this work, the quantitative results are different. This is not surprising as factors such as the uneven spatial distribution of the ground monitors or the nonuniform aerosol vertical distribution are known to affect the correlation between ground- and satellite-data [69]. This issue further justifies the need for the recalibration of the particulate-matter-based soiling estimation method described in the "Methodology" section.

It should be mentioned that the satellite data also show an unusually high cloud cover for the period (0.76 ± 0.10). This is greater than the typical values registered in March of the previous years (0.51 ± 0.19). This phenomenon is not necessarily independent and could be correlated with the occurrence of the dust storm events. Indeed, the dust particles can act as condensation nuclei for warm cloud formation [70]. However, this correlation could not be proved with the available data and is still being investigated by the community [71]. Nonetheless, the combined effect of all the aforementioned factors led to a 31.3 % drop in GHI compared to the expectation, which had serious implications for the performance of PV at national level, as described in the following subsection.

PV performance

As can be seen in the top plot of Fig. 5, the capacity factor, calculated according to Eq. (1), follows a seasonal behaviour in Spain. Indeed, favoured by the higher irradiation and the clearer days, the performance of PV peaks in the summer months. In particular, average values of 24.6

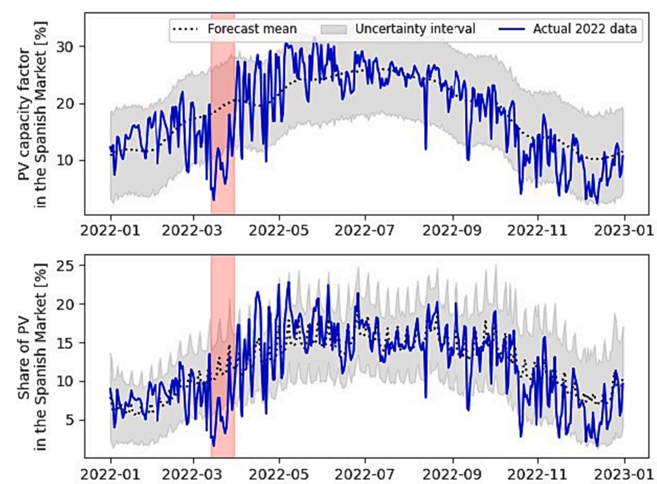

Fig. 5. Top plot: forecasted vs. actual PV capacity factor in 2022. Bottom plot: forecasted vs. actual PV market share in 2022. The red-shaded area shows the period under investigation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

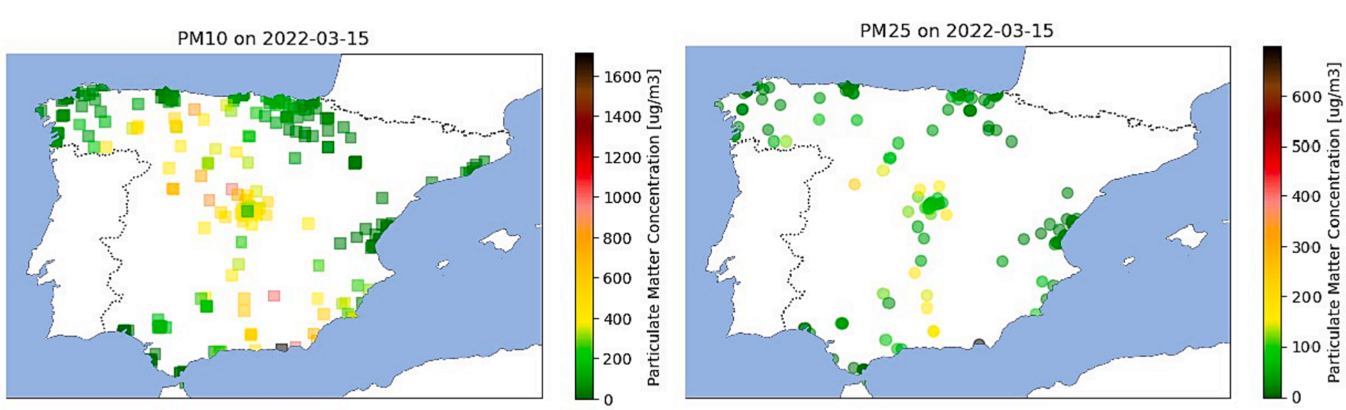

Fig. 4. PM_{10} (left column) and $PM_{2.5}$ (right column) ground-measurements across Spain on March 15th, 2022.

± 1.5 % are typically experienced in between May and August. On the other hand, the average capacity factor drops to approximately 10 % in December.

In March 2022, because of the effects of the dust storms on the irradiance, a sudden drop in capacity factor was registered for PV at national level. Typically, indeed, the PV technology in March had been working at an average capacity factor of 18.9 ± 5.7 % in Spain. However, during the investigated period, the national PV capacity factor dropped to 9.3 ± 4.0 %, resulting in a monthly average of 12.0 ± 4.9 %. The latter is lower than average capacity factors recorded in both February (15.7 ± 3.8 %) and April (21.7 ± 5.8 %) of the same year.

This means that, during the investigated period, the capacity factor dropped by 52.2 %. Remarkably, this reduction surpasses any other recorded reduction in PV capacity factor over a similar 17-day duration in recent years. The second largest recorded drop occurred in March 2018, when the capacity factor decreased by "only" 34.8 % compared to expectations.

As expected, the strongest reduction registered during the investigated 2022 events occurred during the first storm, with an average loss of PV capacity factor of 63 % over a week. Notably, while one-week reductions exceeding 50 % had already been recorded in March 2018 and December 2022, the drop in March 2022 is the most intense one-week reduction since at least 2018.

In addition, it should be noted that, on March 16, the capacity factor was 84.6 % lower than expected, marking this the most significant single-day drop since 2015. Previous extreme single day drops occurred on November 22 and December 20, 2019, and on January 8, 2021, but they spanned from 75 % to 80 %. The analysis of the clear sky GHI proves that these were not due to high aerosols loads, as the clear sky irradiance met the expectations on those days. On the other hand, cloud covers as high as 0.87, 0.91 and 0.77 were found.

Overall, the PV capacity factor drop caused by the first March 2022 dust event was larger than the uncertainty interval on each day from March 14 to 18. During the second storm, the drop averaged to 46.2 % and reached the maximum value (70.7 %) on March 24, which is also among the highest capacity factor reductions registered on a single day since 2015.

In March 2022, the electricity prices in Europe had experienced an unprecedented growth and had reached record-high values. In the second half of 2022, the average price in Spain was 234.9 ± 17.7 €/MWh. This means that, a total of 154 • 10^6 € were lost due to the missed PV production. This corresponds to missed daily revenues of 9.0 • 10^6 €/day. These are about 50 % higher than the daily losses that the whole Spanish electricity sector experienced during the first COVID-19 lockdown [35], when, however, the electricity prices were less than 50 €/MWh and the PV capacity was approximately 40 % lower than in March 2022.

Thanks to the rapid increase in national PV capacity, the penetration of PV in the Spanish electricity mix has also been growing over the years. This can be expressed through the market share, calculated according to Eq. (2), which represents the percentage of electricity consumption that is provided through a specific technology. In particular, the PV market share in Spain went from an average of 3.1 % until 2019 to 8.6 % in 2021. The forecast expected this value to reach an annual mean of 12.1 % in 2022, with monthly averages higher than 15.0 % for the summer months. The analysis of the actual data confirms that a 17.4 % record was achieved in May 2022, and that it was even already overtook the following year. In 2023, indeed, the monthly mean shares in April, May, July and August surpassed 21.0 %.

Fig. 5 clearly shows a drop in market share in March 2022, the period under investigation in this work. Indeed, because of the storm, an average PV production of 38 GWh/day were missed compared to the expectations. This loss consequently lowered the share of photovoltaics in the national electricity mix. In particular, the national PV capacity underperformed continuously from March 14 to March 25. This resulted in an average market share of 7.1 % over the month of March 2022, while it was expected to achieve 10.9 %. This value is below those registered in February and April of the same year, when market shares of 8.7 % and 14.1 % were achieved. In between March 14 and 16, the PV share was lower than 3 %. The minimum market share, 1.6 %, was reached on March 16. Such a low market share value had not been registered since February 2021, when the national capacity was 25 % lower than in March 2022.

It is a well-known fact that the electricity demand changes during the weekday compared to the weekends, due to differences in the daily routines and activities. In particular, since 2015, the daily demand in Spain has been 11 % and 20 % higher during the weekdays compared to Saturdays and Sundays, respectively. This is also reflected in the market share results shown in Fig. 5, where spikes are visible, for example, in the forecast and in the uncertainty range. Because of the lower demand, the share of PV has indeed been generally higher during weekends. The same occurred even during the dust storms, with PV reaching shares 63 % and 130 % higher on Saturdays and Sundays compared to the weekdays.

The analysis of the regional data confirms the previous findings. As can be seen in Fig. 6, most of the losses are registered in the central-southeastern communities. The highest drops, close to 50 %, are found in two communities (Castilla la Mancha and Región de Murcia), which jointly represent 30 % of the national capacity. Also Cataluña registered a reduction in capacity factor of 48.2 % but at the time hosted only 0.3 GW (2 % of national capacity). It should be noted that 93 % of the peninsular capacity was located in just 6 communities, which experienced an average drop of 39.5 %. On the other hand, the northernmost communities were less affected by the March 2022 events. For example, Principado de Asturias and Cantabria registered drops of 3.1 and 6.7 % respectively. However, they typically register capacity factors of 7.7 and 10.5 % in March, and in that period hosted a joint capacity of only 5.1 MW.

Overall, despite the expectations associated to the significant particulate matter concentrations, limited soiling losses, calculated as for Eqs. (6) and (7), were registered during the second half of March 2022 (Fig. 7). This means that, in this case, the effects of the dust storms did not have prolonged consequences on the PV generation. Indeed, the average loss during the period was 0.8 ± 0.5 %. This is much lower that, for example, the typical 3.2 ± 3.2 % loss registered in August. The March 2022 data are in line with the soiling losses registered in the same months of the previous years (1.0 ± 0.4 %).

This lack of a strong soiling effect can be explained by the extraordinary amount of rainfall registered in the investigated period. On average, indeed, each location experienced a rainfall intensity of 3.6 ± 2.4 mm/day, a value that is twice the yearly average (1.9 ± 0.9 mm/day) and 1.6 times the typical rainfall intensity of the same period in the previous years (2.3 ± 1.0 mm/day). Each location, on average experienced more than 8 days of rainfalls > 1 mm/day in the second half of March.

Overall, the present paper shows the impacts that dust storm events can have on the nationwide PV capacity production of a single country. However, it should be noted that Spain was not the only country affected by the investigated dust storms. Indeed, the same events travelled across Portugal and also reached part of Italy. In Portugal, the national PV capacity factor in March 2022 dropped by 37.9 % compared to the same period of the previous years. During the first event, the capacity factor dropped by 44.9 %, with a maximum of 85.5 % on March 16. The second event made the capacity factor decrease by 34.1 %. The drop is bigger than the forecast intensities from March 14 to 17 and on March 20, 23 and 24. The effect was lower in Italy, with significant drops in March 17 and 18, when the national PV capacity factor fell by 47 %.

As can be seen, the proposed methodology can be employed to investigate the effect of dust storms also in additional countries depending on the data available. For this reason, the present analysis should be extended, in future, taking into account more dust storms and

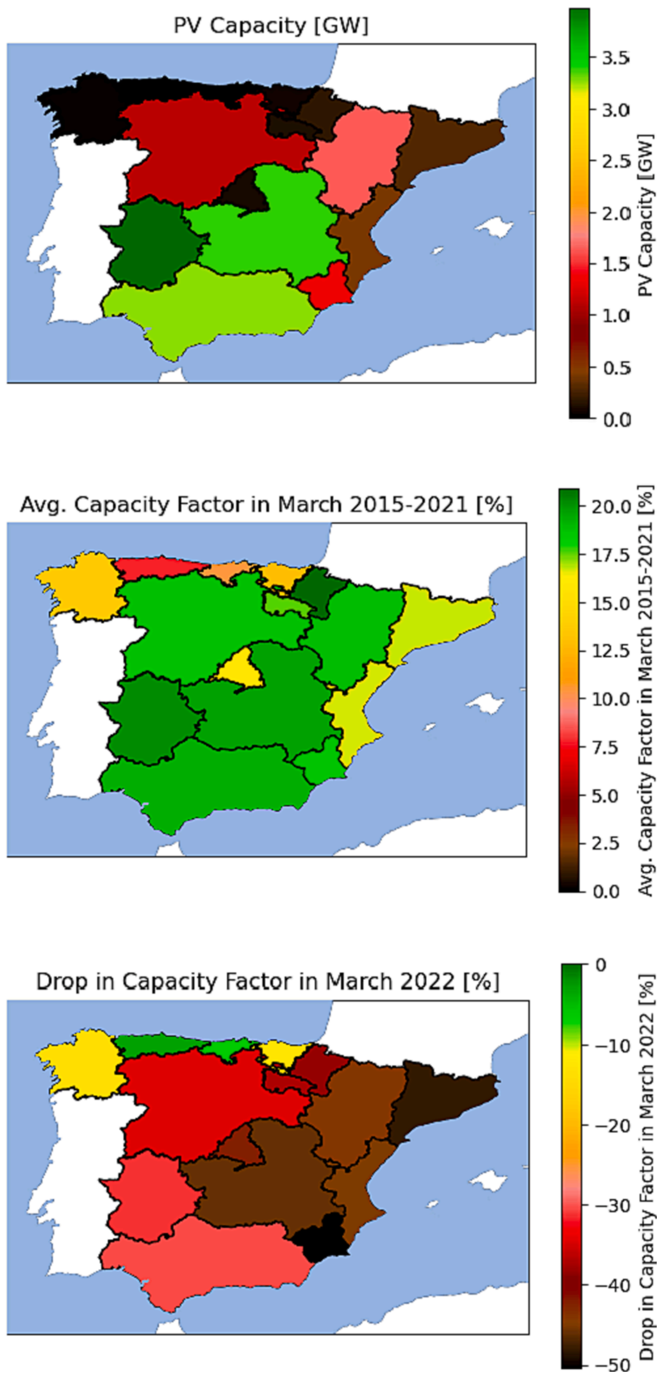

Fig. 6. Capacity, Average Capacity Factors in March 2015–2021 and Relative deviation in Capacity Factor in March 2022 compared to the average in March 2015–2021 average.

more countries, to increase the understanding on their occurrence and impacts. Additionally, the same methodology could be used to assess the impact of additional events, such as wildfires or large volcano eruptions. For example, it has been shown the productivity of the PV capacity can decrease by up to 30 % during smoky days due to wildfire [72]. In light of these results, similar studies should be conducted on more events which can put at risk the reliability of the national grid in high PV penetration scenarios, such as in presence of exceptional aerosol caused by the aforementioned wildfires or large volcano eruptions.

In countries such as Italy, Portugal and Spain most of the electricity is sold through a day-ahead bid-based market competition [73]. This means that the electricity is offered and bought ahead of time and the price is set depending on the difference between supply and demand and on the amount and costs of available energy. Therefore, forecasting the amount of electricity that will be produced by PV is key to get a good estimation of the market price. In this light, services that provide weather forecasts are already employed to estimate the day-ahead PV power production. For example, Solcast produces up to 14 days ahead irradiance and weather forecasts [74]. The National Centers for Environmental Prediction also offers forecasts up to 16 days in advance through its Global Forecast System [75]. PV power production forecasts could be improved by integrating also dust forecasts. This way, also the effects of dust events could be taken into account, given the significant impact they can have on the PV performance. The Barcelona Supercomputing Center [76], for example, regularly produces up to 72 h ahead dust forecasts that can be used for this purpose.

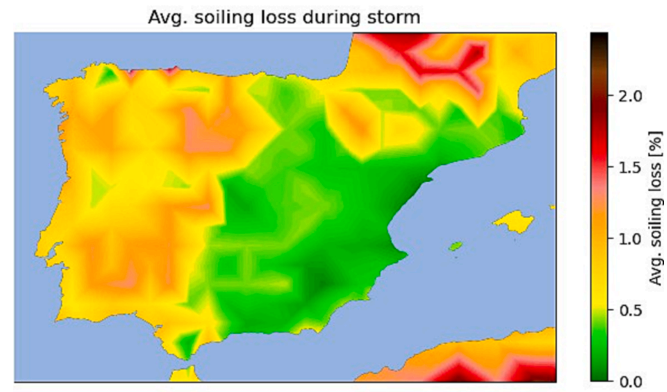

Fig. 7. Average daily soiling loss registered during the investigated period.

Last, it must be acknowledged that extreme events such as those analysed in this work might lead to consequences other than the investigated drop in PV power production. For this reason, future studies should also consider the effects of such events on PV variables like, for example, terminal voltage, and reactive power.

Conclusions

This work presents a first countrywide analysis of the impact of dust storms on the PV generation. The analysis shows that, on a single day, the production of the national PV capacity could drop by more than 80 %. While sudden drops can occasionally occur also because of overcast conditions, the present analysis shows that the effect of the dust storm can last for several days, leading to capacity factors that, over a period longer than two weeks, can be even half of those expected.

The analysis is conducted on two dust storm events that occurred over the Iberian Peninsula in March 2022. In particular, the high concentration of dust and sand particles transported by the storms substantially increased the aerosol optical depth, with a national average even higher than 1 on the worst day, hitting more intensively some of the regions that hosted most of the national PV capacity. In addition, the presence of possibly related clouds further lowered the intensity of the available solar resource, contributing to worsen the aforementioned performance losses. The impact of the investigated events could have been even more severe and prolonged because of the potentially associated soiling. However, the results show that the intense rainfalls occurred during the storms' period kept the modules clean, improving the resilience of the national PV capacity.

Overall, the results of this study confirm one of the potential risks to which national grids are exposed because of the growing PV penetration. Events such as dust storms, indeed, can impact wide areas and therefore significant portions of regional and national PV capacities, temporarily reducing the energy provided by this fast-growing technology.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT by OpenAI in order to improve spelling, grammar, clarity, and general editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Leonardo Micheli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft. **Florencia Almonacid:** Resources, Writing – review & editing. **João Gabriel Bessa:** Conceptualization, Data curation, Investigation, Validation, Writing – review & editing. **Álvaro Fernández-Solas:** Conceptualization, Data curation, Investigation, Validation, Writing – review & editing. **Eduardo F. Fernández:** Resources, Writing – review & editing.

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

Data will be made available on request.

Acknowledgments

L. Micheli's work was supported by Sole4PV, a project funded by the Italian Ministry of University and Research under the 2019 «Rita Levi Montalcini» Program for Young Researchers.

The authors thank Maria Luisa Cancillo Fernandez, Jose Maria San Atanasio, Ana Diaz Rodriguez, Carlos Pérez, Micheal Sicard, Lucas Alados Arboledas, Victoria E. Cachorro Revilla, Margarita Yela González and Alejandro Rodriguez Gomez for their effort in establishing and maintaining the AERONET sites in A Coruña, Badajoz, Granada, Murcia, El Arenosillo and Barcelona.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2024.103607.

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