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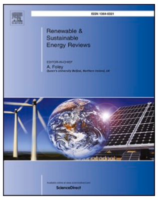

Effect of Saharan dust episodes on the accuracy of photovoltaic energy production forecast in Hungary (Central Europe)

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ABSTRACT

In order to meet global sustainability goals, in particular, the rapid decarbonisation of the energy sector in combination with geopolitical energy security issues, as well as further improvement in regional air quality-the so-called renewable energy sources are becoming increasingly critical and important. Photovoltaic power (PV) generation is clearly the most widely deployed (non-hydro) renewable energy source globally, which still has a significant growth potential in many countries, including Hungary.

However, due to the intermittent nature and the strong dependency of photovoltaic power production on meteorological factors, continuous adjustment of electric power in the electric grid is needed. This, in turn, requires the most accurate forecast of the photovoltaic energy to be produced in the ultra-short term (15 min) and short term (1 day) in order to minimise last-minute and high-price energy acquisition or unplanned kicks-in of gas-fired auxiliary power plants.

In this paper, we evaluate the impacts of large-scale dust transport episodes on the accuracy of forecasts of PV power generation. The numbers and intensities of Saharan dust storm events reaching Central Europe have increased over the last decade, hitting a new record in 2022 with 16 (!) African dust episodes observed over Hungary. We have shown that the semi-direct effect of atmospheric dust particles on high-level cloud formation rather than their direct irradiance-reducing effect is responsible for the reduced accuracies of e short-term (24-h) PV energy production forecasts during these events.

1. Introduction

The energy crisis, fuelled by mitigation-focused climate policy, sustainability concerns and global geopolitics, has fundamentally increased the importance of renewable energy production [1,2]. This is particularly true for countries with a high share of imported fossil fuels in their energy mix exposed to geopolitical risks [3,4].

Beyond the geopolitical energy crisis, renewable energy investments are of particular importance for the long-term prospects of zero-carbon policies. Because of the unresolved storage of electricity at a large scale, there must be a continuous balance between production and consumption of electric energy [5]. This means that it is vital to have the best possible estimate for electric energy production for the short-to-mid-term, which poses a great challenge for strongly weather-dependent renewables. Solar power forecasting is the process of predicting the expected solar power output from a photovoltaic (PV) system over a given time period. This process is important for energy system operators and utility companies who need to ensure that they can meet their consumers' demand for electricity by balancing the supply and demand of energy on the grid. Accurate forecasting is important not only for maintaining grid stability, reducing greenhouse gas emissions, and optimising operational costs. The latter includes heavy penalties imposed upon the difference between the forecast and the energy actually produced.

Proper forecasts can help utilities to reduce the need for kicking-in expensive gas-fired backup power plants and improve grid stability.

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An accurate weather forecast is a prerequisite for predicting solar power generation since the flux of solar radiation absorbed by panels is dependent on the prevailing weather conditions [6]. These data are gathered and predicted using a combination of observations, statistical models, physical models, and artificial intelligence/machine learning algorithms [5,7–11]. These methods can be used alone or in combination to improve accuracy on different time horizons, ranging from short-term (hours) to medium-term (days) to long-term (weeks or months). The time horizon depends on the application, with short-term forecasts being useful for real-time grid operation, while long-term forecasts are more relevant for energy market trading and system planning. In this paper, 24-h PV forecast issues are discussed.

In addition to many other factors (temperature, precipitation, etc.), clouds have by far the most important impact on the flux of solar radiation that reaches the surface, which in turn affects the output of a PV system [12,13]. Therefore, accurate cloud cover predictions are essential for accurate solar power forecasting. Forecast models that include detailed cloud physics take into account factors such as cloud opacity, altitude, and size. These models typically use data from satellite imagery, radar, and ground-based sensors to obtain information on cloud cover and information on cloud properties such as thickness, height, and type.

Atmospheric mineral dust particles can also affect cloud properties such as droplet size and cloud lifetime, which can in turn, affect the flux of solar radiation that reaches the surface [14–21]. Winds can carry dust over long distances and can act as cloud condensation nuclei, which are tiny particles that serve as seeds for cloud droplet formation. However, these effects are not represented in weather forecast models due to their complexity, limited understanding and computer capacity constraints. Aerosols may also have a significant direct impact on solar power output, soiling causes production problems in areas with high levels of air pollution or dust deposition [22,23]. In Central Europe (and Europe in general), atmospheric dust is considered an important factor in the problems of forecasting photovoltaic power generation primarily due to its semi-direct effect on cloud formation; direct effects on radiation are less significant due to the relatively low mass concentrations and low aerosol optical depth values of the dust episodes.

In Europe, atmospheric dust intrusions are primarily connected to Saharan dust events (apart from rare episodes from Central Asia or the Middle East) [24–26]. However, Saharan dust is either ignored or poorly parameterised in the forecast models. Research on these episodes in recent years has shown that both the frequency and intensity of long-range dust storm events in the region are increasing, thus, dust climatological values cannot be reliably used in the models. According to Varga [26], 218 Saharan dust events (SDEs) reached Hungary between 1979 and 2018. In this paper, we provide further information on SDEs and their meteorological background in the area, classified by the same methodology. The output-reducing effect of dust deposition on PV panels is outside the scope of this work. However, it should be noted that dust deposition fluxes have also been increasing in Central Europe in recent years.

It will be shown that the study area has experienced an increase in the number and intensity of Saharan dust storm events compared to the last decades, which have an impact on the cloud formation conditions in the region and thus on photovoltaic power generation. We discuss in detail the extent to which photovoltaic power generation has been reduced during intense dust storm events and how day-ahead forecasts have been affected by errors during these periods. Our results suggest that a deeper understanding of the amount and material composition of particulate matter is needed to improve the accuracy of the forecasts and that the results of short-term dust dispersion simulations should be used in photovoltaic forecast models instead of aerosol climatological data.

2. Material and methods

2.1. Area of study

Hungary, with an area of 93,000 km^2, is located in the Carpathian Basin, which can be described as a relatively closed geographical territory with a low, less segmented relief than its surroundings. As a consequence, there is no significant hydroelectric or wind energy production potential in the region. On the other hand, the relatively high number of sunshine hours (2100–2600 hy^{-1}) supports a high development potential for photovoltaic power generation. As an alternative, only low-grade coal is available from domestic sources for energy production.

At the same time, the country's 20th-century history and the political and economic influence of the former Soviet Union have also had an impact on the energy sector today, with natural gas from Russia continuing to play a significant role in the Hungarian energy mix. In addition, Hungary's single nuclear plant is powered by fuel imported from Russia.

According to data from the Hungarian Energy and Public Utility Regulatory Authority, electricity generation in 2022 was distributed as follows: nuclear energy (15,812 GWh – 44.7 % share of total), gas (8658 GWh – 24.5 %), solar energy (4649 GWh – 13.1 %), coal (3052 GWh – 8.6 %), biomass/biogas (1932 GWh – 5.5 %) and wind energy (605 GWh – 1.7 %).

The total share of sectors with high greenhouse gas (GHG) emissions is still high. Both EU and national climate policy legislation impose obligations on member countries. Thus, Hungary is also required to reduce GHG emissions (by 55 % by 2030 compared to 1990 levels and to achieve net zero carbon emissions by 2050), which can only be implemented by rapidly increasing the installed renewable energy capacities in the overall energy mix (according to Hungary's Climate Protection Law, renewable energy production should make up at least 21 % of gross energy consumption by 2030).

The share of photovoltaics in gross electricity generation in Hungary has increased significantly in recent years. From 0.5 % (141 GWh) in 2015, it increased to 13.1 % (4649 GWh) in 2021, even while overall electricity production increased from 30,360 GWh to 36,120 GWh during the same period. With an eight-fold increase in installed photovoltaic capacities between 2017 and 2021, Hungary had the third highest growth rate in the EU, behind Estonia and Poland which increased from a very low base – IRENA, 2023). The boom in solar investment in Hungary in recent years has made the country having the highest share of photovoltaic energy production in electricity generation in the EU-27 in 2021, just over 10 %. In 2022, the annual photovoltaic energy production amounted to 4.5 TWh (13 % of the total electricity production), which was the third highest in the EU-27 (behind the Netherlands and Greece – [27]).

The boom in weather-dependent intermittent energy production in Hungary is accompanied with the installations of natural gas-fired backup power plants. As there is no publicly available data on the excess costs inferred by inaccurate forecasts of solar energy production, we can only refer to personal communication by officials of the Hungarian Ministry for Technology and Industry supervising PV production. In the year of 2021, the penalty was 372 million Euro for 2 GW of installed solar capacity.

2.2. Identification of saharan dust episodes (SDEs)

To identify SDEs in Hungary, the previously developed and applied databases were completed by using the same methodology. Based on the satellite-borne aerosol data (the standardised values of Aerosol Index of Ozone Monitoring Instrument (OMI—Daily Level 3 Gridded Products; OMTO3d) and Aerosol Optical Depth data of Terra and Aqua satellites (Combined Dark Target and Deep Blue AOD at 0.55 μm for land and ocean - MOD08_D3_v6; MYD08_D3_v6)), possible SDEs were confirmed via a multi-step verification process: (1) the NASA MERRA-2 Area-Averaged of Dust Column Mass Density (M2T1NXAER.5.12.4) numerical simulations to provide independent confirmation of the presence of dust material in the atmosphere ([28] – data were obtained from Giovanni application for visualisation and access Earth science remote sensing data platform (https://giovanni.gsfc.nasa.gov/giovanni/) provided by NASA Goddard Earth Sciences Data Information Services Center); (2) HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory – [29]) backward-trajectory calculations to prove the Saharan origin; and (3) daily visibility-reducing surface weather reports of the potential source areas by Naval Research Laboratory (https://www.nrlmry.navy.mil/aerosol/#aerosolobservations). Aerosol v3.41 subtype vertical profiles obtained from CALIPSO (https://www-calipso.larc.nasa.gov/) were used as another independent confirmation of the atmospheric presence of mineral dust over Central Europe. As mentioned earlier, the methodology of our previous studies was used in this research. It is similar to that used by Gkikas, A. et al. [30], however the spatial resolution of the MERRA-2 Dust Column Mass Density data is lower than that of ModIs Dust AeroSol (MIDAS) global fine-resolution dust optical depth data set. This causes no concern in the present study, as dust storm events have been identified for a relatively large area.

Further information on atmospheric dust dispersion was provided by the NMMB/BSC model dust load and deposition forecasts [31,32], made available by the WMO Barcelona Dust Regional Center and the partners of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) for Northern Africa, the Middle East and Europe.

The synoptic meteorological background of the SDEs were investigated by using mean geopotential height and wind vector maps at 700 hPa via the daily mean composite application of the Earth System Research Laboratory at the United States National Oceanic and Atmospheric Association (NOAA) (http://www.esrl.noaa.gov/psd/) applying the gridded National Centers for Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project dataset [33].

2.3. Granulometric characterisation of saharan dust material

Samples collected from some intense depositional events in recent years provided the opportunity to get detailed particle size and shape information on Saharan dust material. Malvern Morphologi G3-IDSE automated static image analyser (automated optical microscope) was applied. Mineral particles were dispersed by 4 bar compressed air onto the glass slide of the automated microscope with 60 s settling time, and the × 20 objective lens was used, which provided a 40 pixel per μm^2 resolution of the acquired images of each individual particle. 50–100.000 individual mineral particles were characterised for every sample, and circle-equivalent diameter, length, width, circularity, convexity, solidity, and aspect ratio parameters were used in this study to provide particle size and shape data. This granulometric database was completed with light transmissivity values calculated from the grayscale images of particles and correlation scores of measured Raman spectra of selected grains and the mineral reference database, KnowItAll. Size- and shape-distribution curves were calculated on both number, surface and volume basis. Grain number distribution curves are of interest for the potential condensation nuclei involved in cloud formation, while the surface-based ones are of importance for their reactivity [34], which varies with the roughness of the particle surface. Volume (or nearly equivalent mass) based distributions provide information on the amount of particulate matter, which is relevant to determine the amount of deposited dust (providing information on dust addition to soil formation or nutrient transport into oceans, or even soiling [dust accumulation on PV panels]). Simple mathematical operations can perform conversions between the different approaches, but distributions derived from numerical data of individual particles are typically more accurate than those calculated from the data series of an inverse method (e.g., volume-based distributions derived from laser scattering).

2.4. Clouds

It is known that in clouds with a given water content, increased fine-grained dust concentrations lead to an increase in the number of condensation and ice-forming nuclei, resulting in the formation of smaller ice crystals. Their detection can be monitored from satellites. EUMETSAT's geostationary Meteosat Second Generation (MSG) Convection RGB combines the brightness temperature difference (BTD) between the WV6.2 and WV7.3 channels (on red), the BTD between the IR3.9 and IR10.8 channels (on green) and the reflectance difference between the NIR1.6 and the VIS0.6 channels (on blue). Small ice particles appear bright yellow in this colour scheme.

2.5. PV data sources

The ratio of actual electricity generation per production type based on gross operation control measurement data and day-ahead forecast and actual solar power plant generation data were obtained from the publicly available official reports of Hungarian Independent Transmission Operator Company Ltd (https://www.mavir.hu/web/mavir-en/hungarian-power-system-actual-data).

3. Results

3.1. Identified SDEs in 2022

The previous data on Saharan dust storm events in Hungary (1979–2018 in Ref. [26]) were updated and extended with additional years (2019–2022) following the same methodology. Thus, we now have information on the long-range dust storms affecting the region for the period 1979–2022 (Fig. 1.). The 260 SDE data sets for the 43 years under study show that the number of dust storm events has increased significantly over the last decade, and there have been significant changes in the seasonal distribution, with more and more intense winter dust storms reaching Hungary. The annual number of SDEs increased significantly after 2010 (n = 10–12) compared to the previous (1979–2010) average (4.2). In comparison, 16 SDEs were identified in 2022, of which significant deposition events occurred several times and were regularly reported in the Hungarian press.

These dust storm events are typified by their synoptic meteorological background. A detailed description of each type can be found in Refs. [25,26]. Dust-laden air masses drifting towards Europe in the southerly flow on the foreside of the atmospheric trough over western Europe are classified as Type-1. Typically, dust transport episodes associated with Mediterranean cyclone vortices are classified as Type-2, while the relatively rare SDEs drifting over the Atlantic and arriving with westerly winds are classified as Type-3.

The backward-trajectories calculated by the HYSPLIT model provide the opportunity to determine the path, length and height of the dust transport governed by the synoptic situation, as well as the possible source areas (Fig. 2 and Appendix-Fig. 1.). The dust sources were typically associated with the north-western Sahara, with the intramontane basins of the Atlas, the dust sources of the southern foothills of the mountain range, and the area around the Tunisian chotts being the main dust-emitting regions during these events. Dust transport was sometimes along seemingly unusual paths, with dust material reaching Central Europe not directly from the south but typically at higher altitudes from the NW. Previously, the frequency of these Type-3 events was estimated to be about 10 % of all SDEs [26].

In the context of synoptic meteorological situations, it should be emphasised that the dust flows were mainly associated with large-scale cyclones, which caused intense cloud formation in the affected regions.

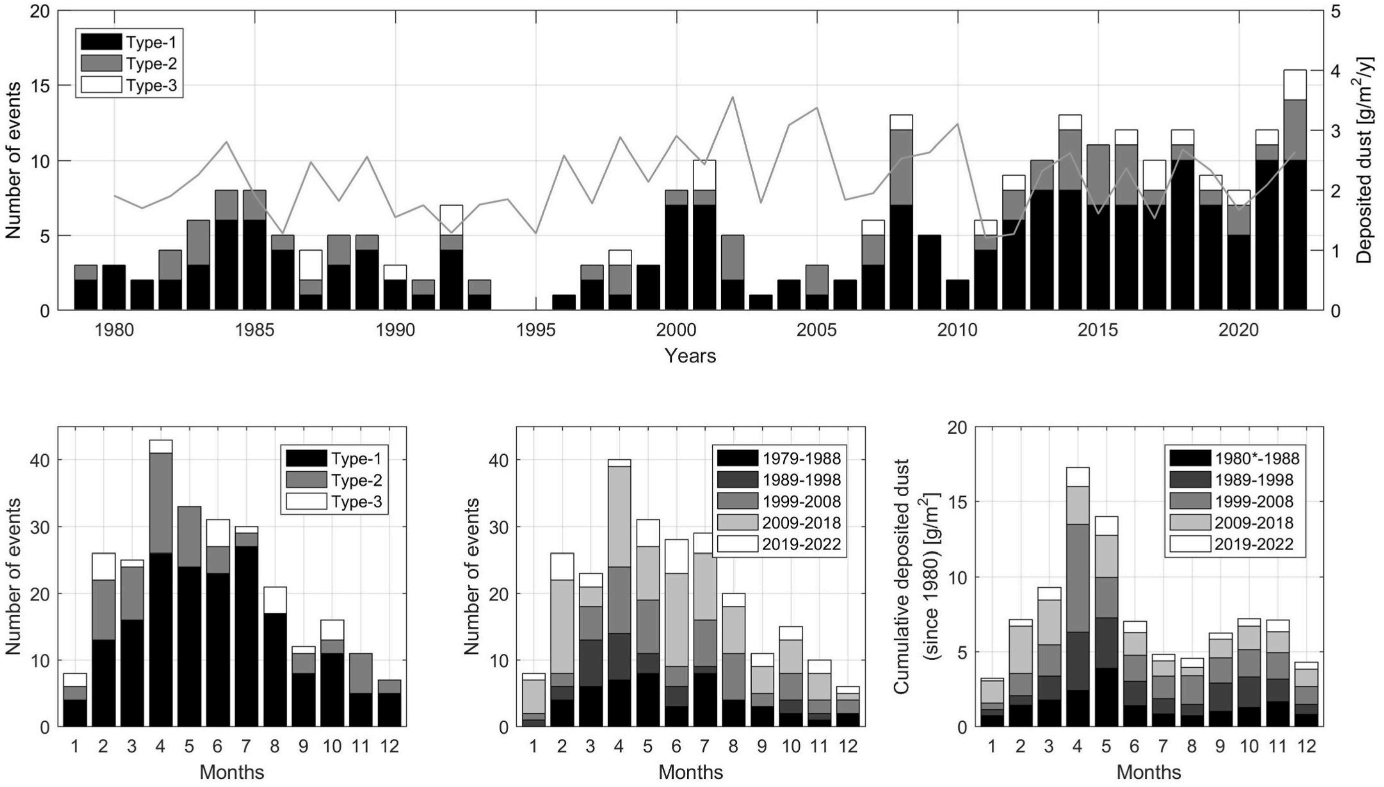


Fig. 1. Annual and monthly frequencies and deposition rates of Saharan dust events in Hungary.

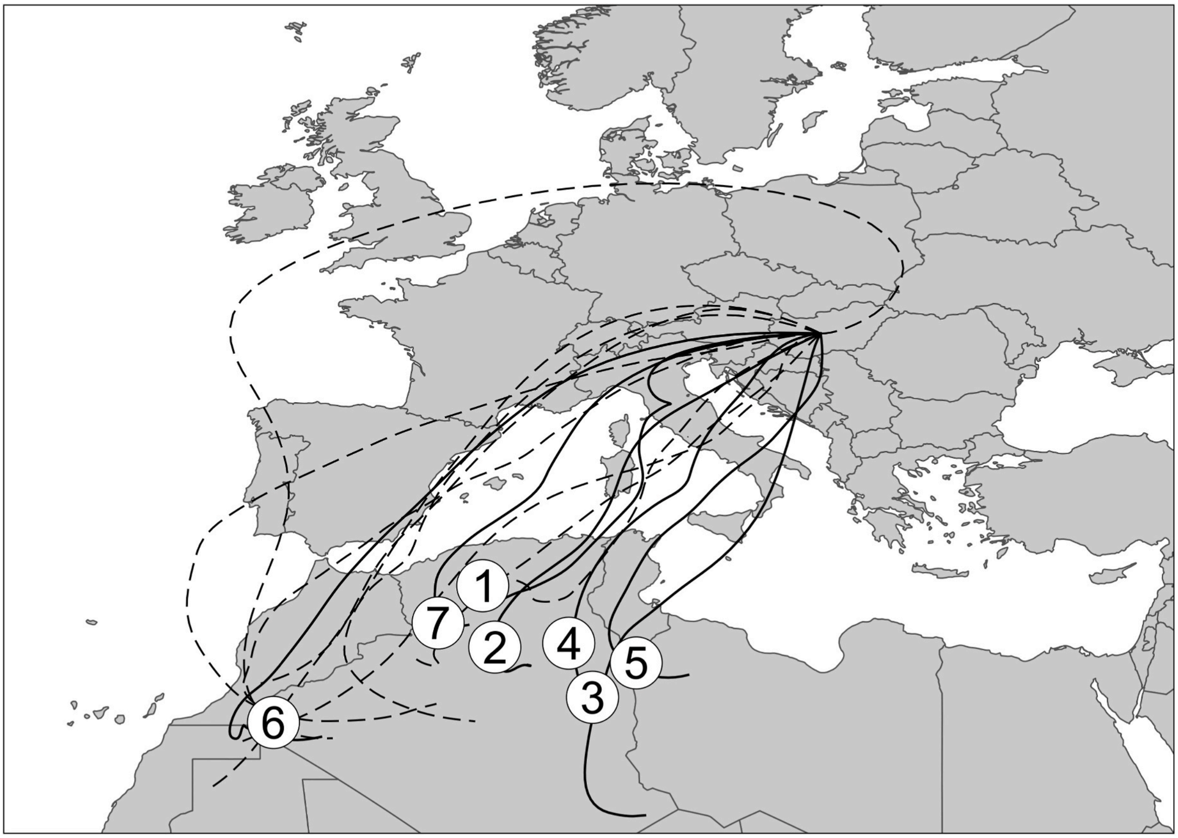


Fig. 2. Backward trajectories of SDEs in 2022; episodes with intense effect on PV production (INT PV episodes) have been highlighted and numbered.

3.2. Transported dust material

The typical grain size of mineral dust samples collected during Saharan dust depositional events in the Carpathian Basin is rather variable. The relatively wide intervals of grain size distribution ranged from a few microns to more than 100 μm. In terms of magnitude, the mode sizes also varied between 10 and 100, indicating granulometric heterogeneity (the distribution curves of 10 samples from the spalled dust from recent years are shown in Fig. 3.).

The particle shapes of the transported and deposited particulate matter were also variable. The images of selected individual particles are shown in Fig. 4 clearly reflect that the silt-sized windblown particles are far from spherical. The shape distributions also fell within a relatively wide range (typical values for recent years: aspect ratio, circularity, convexity).

Raman spectroscopic results of individual grains indicate that quartz and feldspar grains dominate the deposited dust samples, and dolomite, calcite and gypsum grains were also identified. A close relationship between mineral composition and shape parameters has not yet been detected, with all mineral phases being characterised by a non-spherical character.

3.3. PV power production and SDEs

PV power production data, the difference in PV power output between 24-h forecast and actual values, and area averaged dust column mass loads are shown in Fig. 5. (The photovoltaic production data are presented in hourly resolution so that the power output and energy produced can be more easily read from the graphs.) It can be seen that, at times, relatively stable (with a specific seasonal pattern) output values fall back significantly. This is a natural process, depending primarily on the cloud cover. However, it is also striking that in almost all cases, there are large declines in PV power production during SDEs, and it is also apparent that the forecasts during these events show significant discrepancies; during almost all SDEs, higher PV power outputs were forecast than actually realised (see in detail in Fig. 6).

For some SDEs, both the decline in PV power output and, in almost all of these cases, the inaccuracy of the forecast were significant. These intense episodes occurred on 15–16 March; 29–31 March; 21–22 April; 5–6 May; 18–20 August; 14–15 September; 24–25 October (Fig. 6.). In some cases, power output declined by more than 1 GWh from one day to the next. During the March and May episodes, the forecast bias exceeded 4 GWh (over the 72-h periods analysed per episode), which required vast-scale interventions from grid operators.

3.4. Cloud cover and solar irradiance attenuation

Of the atmospheric processes underlying the decline in PV production, the impact of cloud cover is of particular importance. The dust load maps of the Barcelona Supercomputing Center's Monarch model clearly show the regions affected by dusty air masses, while satellite images show the presence of thin cirrus clouds right in the foreground of the air masses with the highest dust concentrations. In the vast majority of the intense dust storm events studied light yellow and orange areas could clearly be observed in the Meteosat 0° RGB Composites Convection images, indicating the presence of large amounts of small ice particles in the cloud cover over the study area (Fig. 7.).

4. Discussion

4.1. Saharan dust material in Central Europe (granulometry and mineralogy)

The role of mineral dust in cloud formation depends on the particles' size, shape and mineral properties, with many uncertainties. This paper discusses in detail how different meteorological conditions, seasonality, source area and material quality of dust storm events affect PV forecasting. Saharan dust storm events can have seasonally different effects on cloud formation, mainly due to the heterogeneous nature of local weather conditions and dust storm events. The source regions of the Saharan dust storm events that reached Hungary and Central Europe are relatively well known, but the general sedimentary geology, soil, and geochemistry of these emission regions cannot be said to be fully documented. The main sources of dust are associated with areas in the north-western Sahara, which are located in the endorheic basins of the Atlas Mountains, on the foothill surfaces of the southern foreland of the mountain range, and in the chotts region to the east. Occasional dust storm events, which periodically transport dust towards Europe from the dust source areas fed by wadies on the eastern foothills of mountain ranges running parallel to the Western Saharan coastline, are observed.

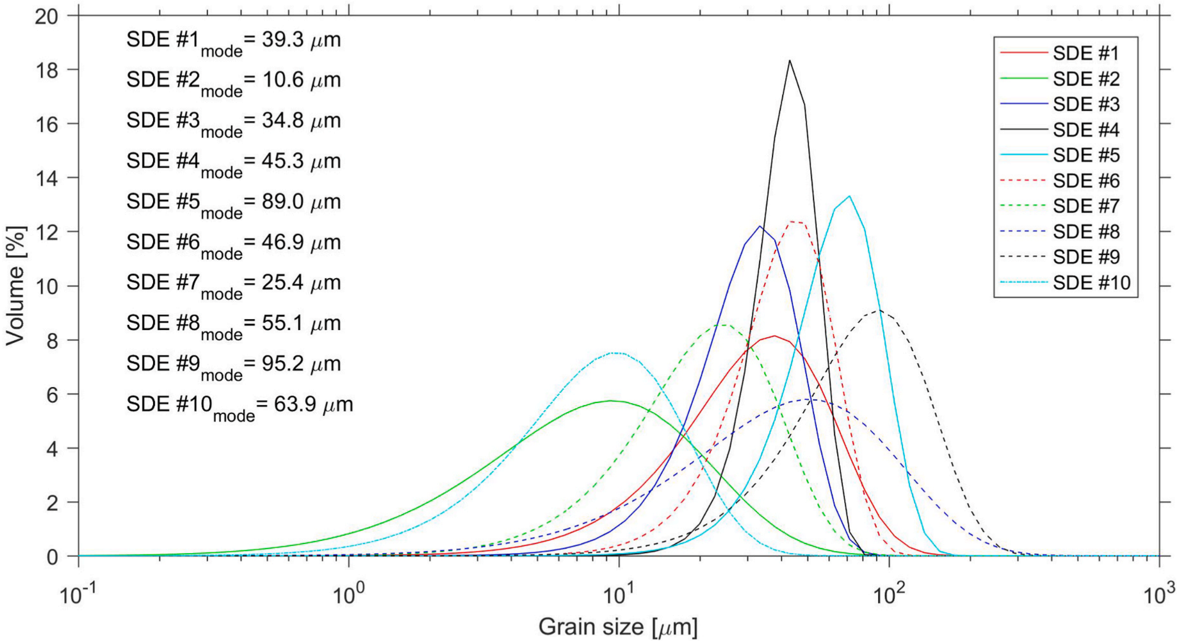
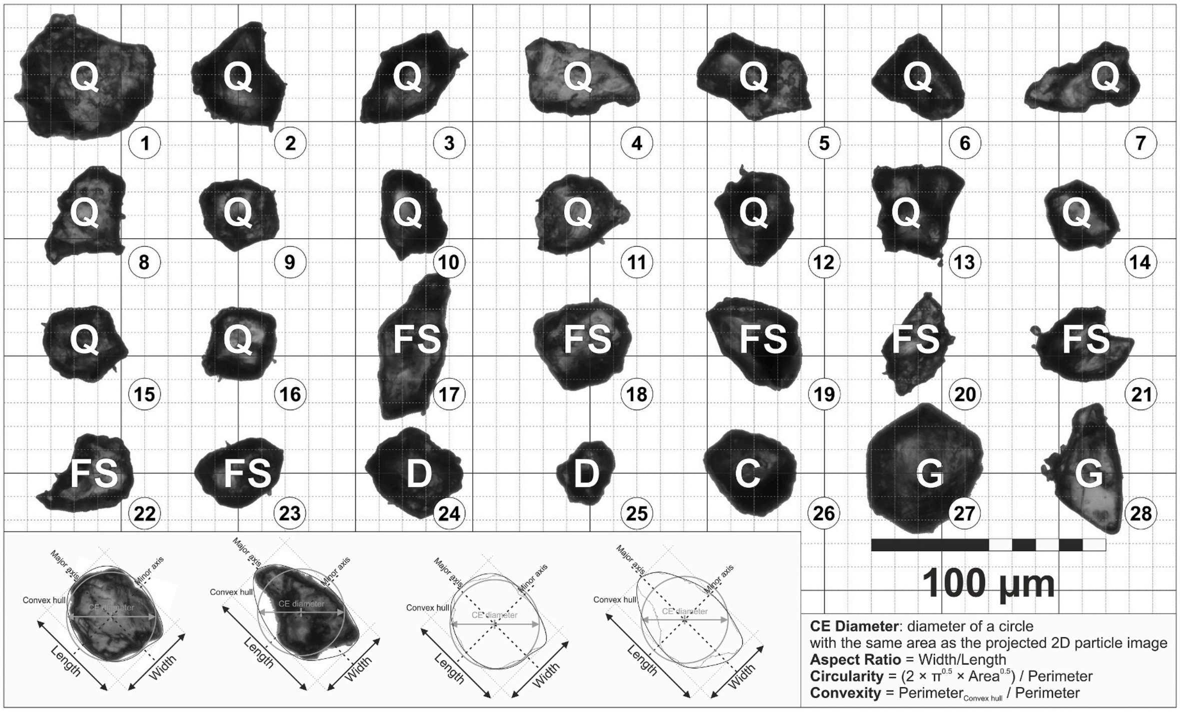


Fig. 3. Volume-based grain size distribution of samples from 10 different Saharan dust depositional events.



CE Diameter: diameter of a circle with the same area as the projected 2D particle image
Aspect Ratio = Width/Length
Circularity = $(2 \times \pi^{0.5} \times \text{Area}^{0.5})$ / Perimeter
Convexity = $\text{Perimeter}_{\text{Convex hull}}$ / Perimeter

Fig. 4. Size, shape and mineralogy of selected silt-sized particles from 2022 Saharan dust depositional events to demonstrate the granulometric heterogeneity of atmospheric dust (Q: quartz; FS: feldspar; D: dolomite; C: calcite; G: gypsum).

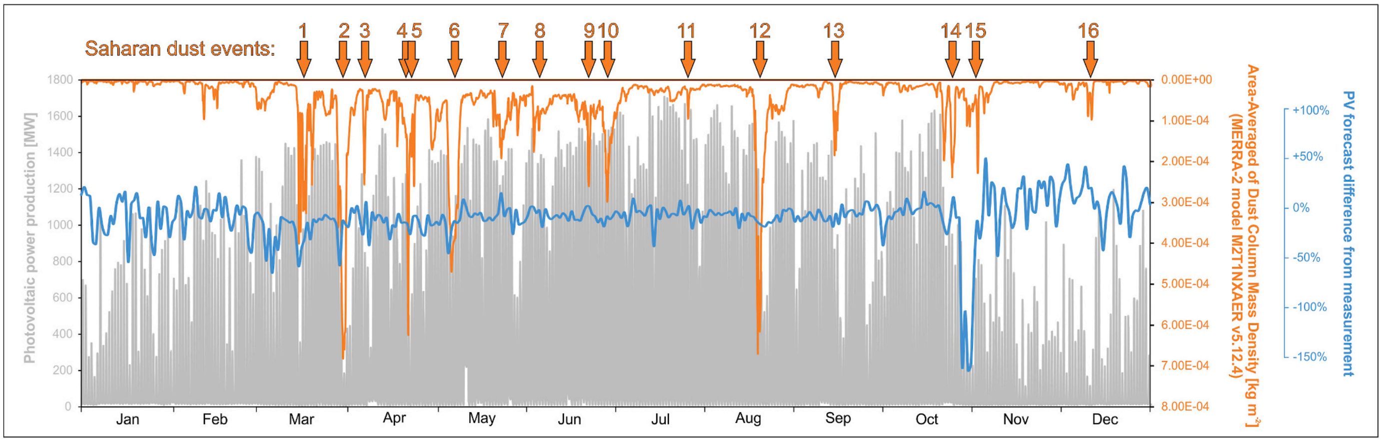


Fig. 5. PV power production,24-h forecast accuracy, dust column mass loads in the calendar year of 2022. Identified SDEs are numbered and marked with brown arrows.

Although the source rocks have heterogeneous characteristics, the most common minerals found in the literature are quartz, feldspars, calcite, dolomite, gypsum and clay minerals (kaolinite, illite, smectite, palygorskite) [35–37].

Granulometric analyses of the collected Saharan dust samples have shown that the simplified dust parameterisation used in dust dispersion and deposition models and in meteorological and cloud physics calculations of Saharan dust in general does not reflect reality. In the vast majority of dust models, mineral dust particles are assumed to be spherical and typically less than 20 μm in diameter. In contrast, in reality, much larger dust particles can travel up to thousands of kilometres from the source areas. And their shape is non-spherical.

Previous descriptions of the dust material of SDEs in Hungary are almost identical to the list of mineral phases listed above [38]. Regarding the granulometric characteristics, the typical grain size encompasses a large range. Sometimes, the equivalent diameter of the settled particulate is less than 10 μm, while in other cases, a high proportion of grains larger than 60 μm can be observed. This value is significantly higher than previous Saharan dust particle size data recorded in Europe [39–42]. However, over the last decade, a number of publications have reported the presence of large dust particles over long distances [43–47], and this research also confirms their presence.

4.2. *Cloud formation and mineral dust*

During the dust storm events, it was not the direct effect of atmospheric dust (i.e. increased aerosol optical depth) that was assumed to play a major role in the drops in PV power output but primarily their indirect effect (i.e. the dust particles as ice nucleating particles (INPs), and cloud condensation nuclei (CCNs) [48–52]. Increased atmospheric mineral particle number concentrations can lead to the formation of more, but smaller, ice particles and cloud droplets for a given amount of

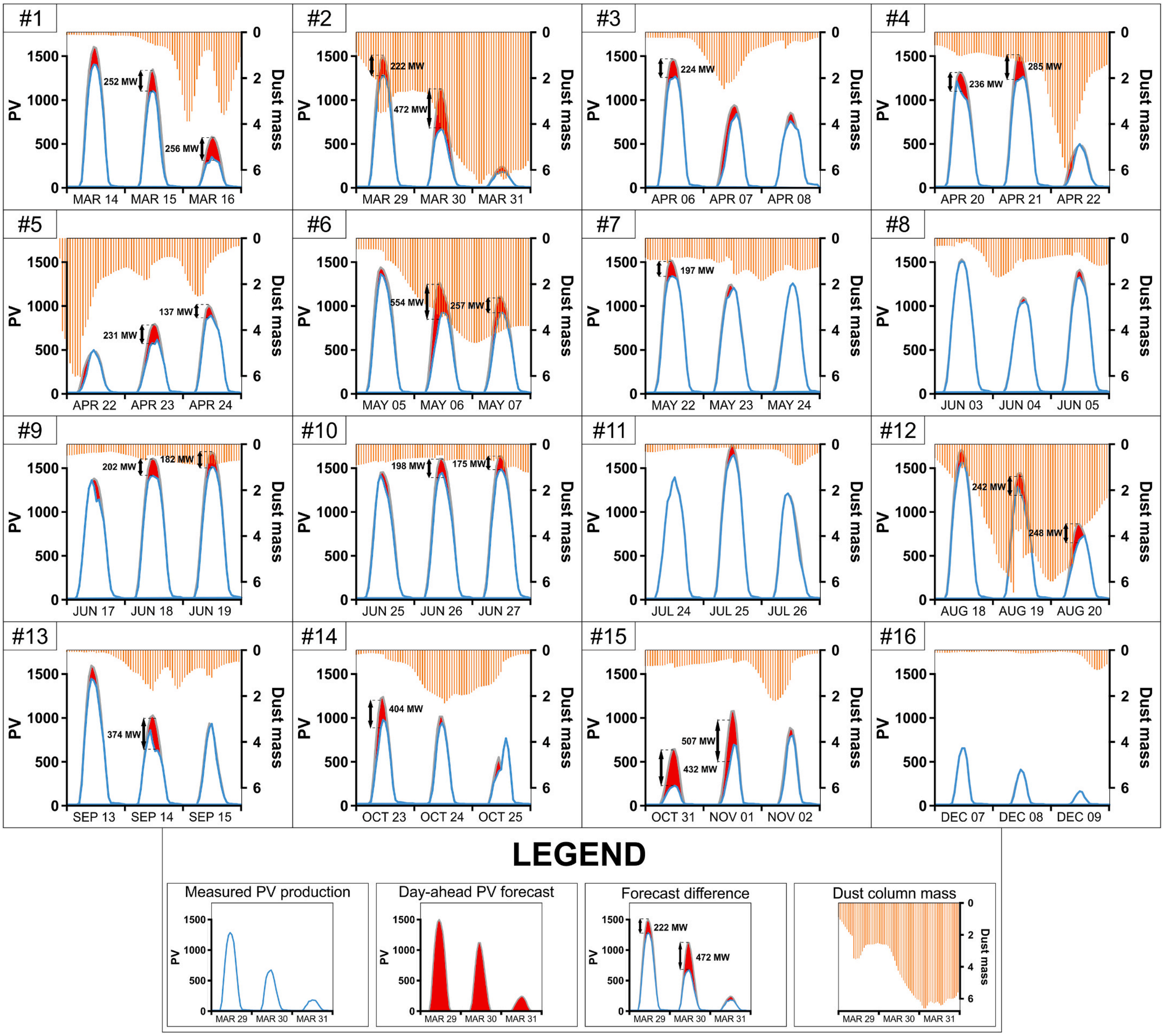


Fig. 6. Actual PV power output and forecast values, and dust column mass loads on specific SDE days in 2022.

water vapour [48,53–56]. However, if the amount of dust, its properties and the dominant mechanisms of the different mineral particles in cloud formation are incorrectly parameterised in the models, the predictions will not be accurate [57].

For the quantification of atmospheric particulate matter, accurate knowledge of the particle size is of particular importance since errors in quantification will most likely be caused by underestimation of particle size due to the cubic relation between diameter and volume [16,58]. Mineral grains larger than 20 μm in diameter) are notparameterised in most dust models [26,59]. Furthermore, the assumption that dust grains are spherical can also affect the volume estimates [34,60,61]. A number of studies have been published in recent years, which, together with our results above, illustrate that the size of mineral dust particles carried by winds, sometimes over large distances, can exceed the upper limit used in dust models by an order of magnitude.

The assumption that dust particles blown out of desert areas cannot play a major role in cloud formation also comes from an oversimplified view that only quartz particles are able to be transported over long distances. This, being insoluble in water and non-wettable, can only play a role in the formation of ice crystals and, hence, cirrus clouds. Our results show that the Saharan dust reaching the Carpathian Basin has a wide range of mineralogical characteristics, similar to the results of other studies.

The problem of cirrus formation and dusty cirrus in Saharan dust-bearing air masses is described in detail by Ref. [57] Seifert et al. (2023). Referring to EUMETSAT case studies [62–64], the authors analyse that extended cirrus cloud decks form during Saharan dust events in Europe, which are not observed during similar synoptic patterns without SDEs. These are challenges in numerical weather prediction and climate models, they are not able to predict dusty cirrus at all, which is due to the fact that they are not run with real-time atmospheric dust data, but they are fed from aerosol climatological databases. Global aerosol and chemistry models predict dust reasonably well, but they do not take into account aerosol-cloud interactions. Research has also shown that quartz grains affect not only ice formation and cirrus formation, but also mixed-phase clouds [65].

In addition to the poorly quantified effect of quartz (the dominant Saharan dust component in cloud formation), we can see from the

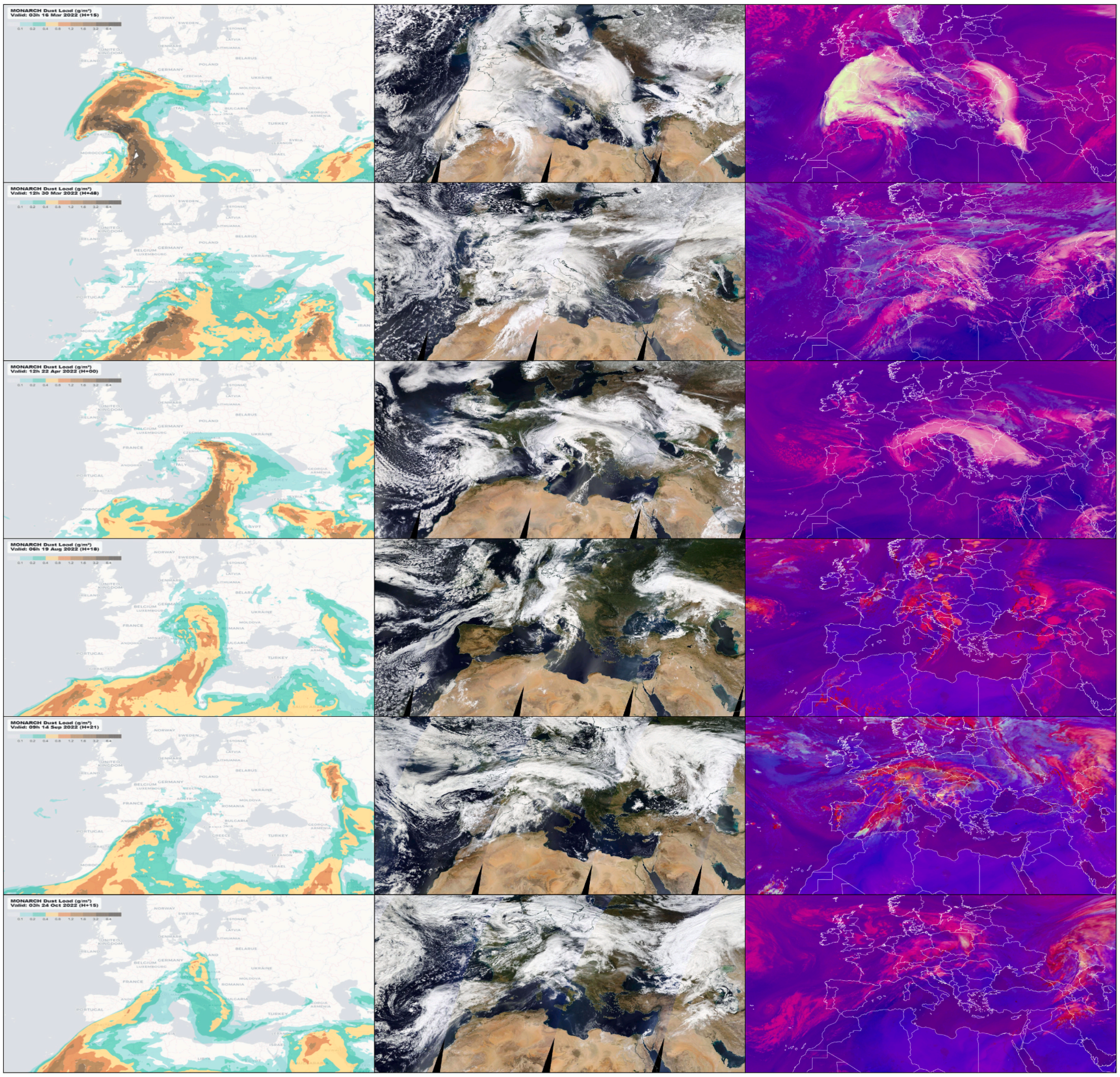


Fig. 7. BSC Monarch dust load numerical forecast (WMO Barcelona Dust Regional Center and SDS-WAS), NASA Terra MODIS True Color and Meteosat 0° RGB Composites Convection images of selected SDE days with significant PV production decline and enhanced cloud formation.

mineral composition data that it is not the only component to be considered [66,67]. The feldspars, calcite, dolomite and clay minerals also have an effect on indirect effects of the particles. Clay minerals are minerals long recognised as cloud and ice-forming nuclei due to their smaller size and, hence, longer atmospheric residence time and hydrophilic properties [54,68,69]. Carbonates are also active condensation nuclei due to their water solubility and wettability, and their atmospheric residence time makes them even more suitable for cloud formation. Reactive trace gases, via their heterogeneous reactions, can increase the CCN activity of carbonate minerals; the hygroscopicity parameters of products of calcite ageing (e.g. calcium nitrate) are significantly higher than those of pure minerals [70].

In recent years, a number of studies have been carried out on the importance of INP and CCN of different feldspars [65,71,72]. Given their relatively high abundance and the ice nucleation ability of K-feldspar (about two orders of magnitude greater than that of quartz grains – [73]), it is clear that they have a significant impact on cloud formation.

Effects of atmospheric ageing of mineral particles resulted a significant overall increase in the ice-nucleating activity of single grains in laboratory experiments [73], while the contribution to INP concentration of the most abundant quartz particles increased significantly at low temperatures. During the meridional Saharan dust transport to higher latitudes, the dust-saturated air masses affect increasingly cooler regions, reaching the critical temperature of −30 °C quickly, especially at higher altitudes. In this range, quartz will become dominant. The SDEs associated with the observed most intense PV production drops typically did not occur in summer, making it even easier to reach critical temperatures.

The importance of non-spherical grain shapes in cloud formation may be similar to that of atmospheric ageing since an increase in the reactive surface area of the grains is associated with the irregular shape. Compared to the number of papers on the mineralogical properties of Saharan dust, the number of papers on the shape properties of dust particles is significantly smaller. The effect of the shape of the desert dust-derived INPs and CCNs on cloud formation has not yet been explored in the scientific literature.

Overall, our results suggest that a deeper understanding of the changing transport patterns and properties of Saharan dust reaching Europe, the amount and material composition (size, shape and mineralogy) of particulate matter is needed to improve the accuracy of day-ahead PV production forecasts. Instead of aerosol climatology data, the results of short-term dust load and transport simulations should be used in photovoltaic forecast models.

5. Conclusions

In this paper, we have demonstrated a negative correlation between national PV power output and the occurrence of Saharan dust episodes in Hungary in the calendar year of 2022, which was characterised by record-high photovoltaic energy production as well as the highest number of Saharan dust episodes in the records. Our work highlights one of the major sources of concern for accurately predicting PV energy generation over the mid-term (24 h): the effects of wind-borne mineral dust. We point out the need to improve the parameterisation of factors that have not been taken into account or have been poorly/overlooked in order to improve the forecast accuracy, which is essential for grid stability, greenhouse gas emission control, as well as sustainability and profitability of PV energy production.

Of the 16 SDEs identified in Hungary in 2022, about half of the events showed a marked (up to a few GWh over the period of 72 h) drop in PV generation compared to similar synoptic conditions without dust episodes, all of which were significantly underestimated in the 24-h forecasts. We showed that atmospheric dust loads (concentration, aerosol optical depth) alone would not explain such drops in power production, but rather, the indirect effect of dust (i.e. its role in high cloud formation) may be more significant.

Particles of different sizes, shapes, and mineral compositions, such as ice and cloud-forming nuclei, are active components of the atmosphere. In this article, we have shown that the Saharan dust that reaches Europe has a wide variety of properties. This is important because the parameterisation of dust in both climate and direct PV production forecast models is fraught with uncertainties in many aspects. The amount and particle size of transported dust are typically grossly underestimated, and the mineral compositions and particle sizes are overly simplified in the simulations. But an even more severe shortcoming is that the models are not fed by actual atmospheric dust observations (forecasts) but only by date from aerosol climatological databases. This in itself causes problems in the projections, but the problem is further compounded by the changing patterns of Saharan dust transport to Europe due to climate change. Both the frequency and intensity of dust storm events have been increasing in recent years. The increasing meridional transport of dust towards higher latitudes enhancing the formation of high-level clouds and the lack of their real-time parameterisation into weather forecast models lead to higher inaccuracies in the 24-h forecast of PV power output rendering grid operations less effective and costlier in the future. According to the communication of Hungarian Ministry for Technology and Industry supervising PV production, in 2021 the penalty was 372 million Euro for 2 GW of installed solar capacity. These costs are expected to increase further in the future as capacity increases.

Thus, further research is needed in order to reduce the bias associated with PV power production forecasts and make the energy sector more sustainable. In addition to expanding our knowledge of dust volume and composition (size, shape, mineralogy), the focus should be on refining the mineral dust parameterisation in models. Short-term atmospheric dust forecast products, which could be used in a cost-effective way, should be used instead of the aerosol climatology data generally used.

CRediT authorship contribution statement

György Varga: Conceptualization, Formal analysis, Writing – original draft. **Fruzsina Gresina:** Formal analysis, Investigation. **József Szeberényi:** Methodology, Resources. **András Gelencsér:** Conceptualization, Writing – original draft. **Ágnes Rostási:** Conceptualization, Formal analysis.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114289.

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