

Article

Atmospheric Forcing on Solar Energy in Complex Terrain: A Digital Twin Assessment in an Intermontane Basin in Southern Balkans

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Abstract

The decentralized deployment of photovoltaic (PV) systems in urbanized polluted mountainous basins faces unique challenges due to complex topography, persistent cloud cover and winter smog conditions. This study quantifies the atmospheric impact of localized winter haze/smog and Saharan dust intrusions on PV performance in the intermontane basin of Ioannina, NW Greece. By integrating a Digital Twin (DT) methodology with real energy production data, two PV plants were evaluated, a ground-based and a rooftop installation, to isolate the energy deficits caused by aerosol attenuation. The DT model demonstrated high accuracy ($R^2 = 0.847$) against actual power generation data for Koutselio and $R^2 = 0.865$ for Mpafra PV plants, while MBE was near zero for both sites (-0.008 kWh and -0.139 kWh, respectively). Error analysis revealed that the highest modeling discrepancies occurred during scattered clouds and intense winter haze conditions, primarily due to low spatial resolution of CAMS that fails to adequately capture localized biomass burning (BB) events. Despite the reduction in direct sunlight during extreme winter BB events, results indicate that the overall energy loss is mild. This operational stability is primarily due to the ability of c-Si modules to effectively utilize near-infrared radiation, which penetrates the low-level haze layer, alongside the thermal efficiency gains provided by low early-morning temperatures. Crucially, the installation geometry may influence system vulnerability. Direct comparisons revealed a minor power deviation of -4.8% for the ground-based Koutselio plant, while for the Mpafra site, there was a $+3.2\%$ production surplus likely linked to the high sky-view factor the rooftop installation has, which manages to capture isotropic diffuse irradiance. However, the low CAMS resolution may misclassify the haze events within the basin, further contributing to these discrepancies. On the contrary, Saharan dust intrusions caused broadband light attenuation, dropping the power production significantly on both installations. Ultimately, this research provides critical insights into the resilience of solar systems under strong air pollution events

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within polluted valleys in Southern Balkans, highlighting the connection between panel design and atmospheric attenuation.

Keywords: solar energy; Digital Twin; winter haze; Saharan dust; atmospheric optical attenuation; radiative transfer model; NW Greece

1. Introduction

In intermontane cold regions, high heating demands often lead to severe energy poverty, forcing a heavy reliance on biomass (wood, biofuel) combustion that triggers persistent winter smog episodes [1]. To mitigate this vulnerability, a transition toward decentralized energy systems is increasingly favored over utility-scale infrastructure, which frequently encounters intense social resistance due to landscape degradation and inequitable benefit distribution [2–4]. With public consensus prioritizing the preservation of pristine highlands and the integration of energy infrastructure into developed peri-urban areas [5], small-scale solar photovoltaics (PV) managed by local Renewable Energy Communities (RECs) offer a viable pathway for poverty alleviation [6]. However, the perceived unreliability of solar resources under heavy smog and winter haze events or under continuous cloudiness during wintertime remains a significant barrier to the adoption of these localized networks [7–9].

Urbanized mountainous valleys epitomize these modeling challenges, as their geographical confinement dictates high spatial variability of pollutants and limits natural ventilation [10,11]. The intermontane basin of Ioannina, NW Greece, serves as an ideal example of such environment in the southern Balkans. Lacking a natural gas distribution network, the heavy reliance on biomass (wood stoves and fireplaces) and heating oil for residential space heating intensifies localized smog within the lower boundary layer [12]. Trapped within this confined volume, anthropogenic emissions are dominated by carbonaceous aerosols, with wintertime fine particulate matter (PM_{2.5}) consisting almost exclusively of light-absorbing Black and Brown Carbon (BC, BrC), mainly from residential wood burning (RWB) emissions [13,14]. This dense carbonaceous aerosol loading significantly alters the atmospheric chemical composition, radiative effects and optical depth [15]. The high PM_{2.5} accumulation poses a major threat to human health, as concentrations frequently exceed safety limits established by the WHO and the European Union [16,17], while the water-soluble BB aerosols and Polycyclic Aromatic Compounds may have a significant oxidative stress [18]. Ioannina was ranked by IQAir as the most polluted city in Greece for 2024, with wintertime PM_{2.5} concentrations reaching up to 50% higher than those recorded in the Athens metropolitan area of nearly 4 million residents [19,20].

Beyond public health, these high BB-laden atmospheric conditions may significantly affect the energy sector. Recent studies have shown that Ioannina has an untapped rooftop PV potential of 1.86 km² (417 MW), capable of producing 548 GWh annually to meet the city's entire domestic energy demand on an annual energy balance basis and reduce CO₂ emissions by nearly 360,000 tons [21]. However, this annual net-balance does not guarantee real-time energy autonomy, as the performance of PV systems in the basin is modified by both ambient temperature fluctuations and spectral optical attenuation [22,23]. Accurate modeling and forecasting solar irradiance in topographically complex areas remains a significant scientific challenge [24]. The solar resource in these regions exhibits massive spatial and temporal heterogeneity dictated by severe terrain shading and localized atmospheric attenuation [25]. Traditional methodologies, such as spatial interpolation from sparse radiometric networks, are often inadequate because they fail to capture local-scale emission sources, atmospheric dynamics and horizon obstructions [26]. Furthermore, re-

cent comparative studies demonstrate that advanced machine learning forecasting models struggle significantly in mountainous locations due to the pronounced atmospheric variability and rapid transitions in sky conditions [27]. These limitations highlight a critical research gap: regional-scale models cannot effectively resolve the micro-scale optical attenuation trapped within narrow polluted valleys [28–31]. Consequently, highly localized, data-driven frameworks are required to isolate specific aerosol concentrations from topographical noise. Recent studies in diverse Greek mountain environments have already highlighted that ground-based spectral solar irradiance, combined with radiative transfer modeling, is essential for accurately retrieving aerosol optical properties, where satellite data lack persistence due to complex terrain and cloudiness [32].

Given these extreme environmental complexities, Ioannina basin represents an optimal case study for investigating the impact of localized haze during winter on decentralized solar energy performance. To address the knowledge gaps discussed above, this study introduces a data-driven Digital Twin (DT) framework designed to quantify the specific impact of localized winter haze and Saharan dust on PV performance. It should be noted that the DT was used here as a diagnostic and attribution tool rather than a real-time operational forecasting system. Its methodological novelty lies in bypassing the spatial limitations of conventional satellite models by establishing a site-specific empirical baseline under pristine atmospheric conditions. By integrating empirical power generation data from two operational PV plants—a ground-based (Koutselio) and a rooftop system (Mpaфра)—with high-resolution libRadtran simulations, this work aims to isolate the energy deficits caused by localized atmospheric optical attenuation, evaluate the spectral resilience of c-Si modules under severe smog, and assess the role of installation geometry in mitigating generation losses. Despite the increased biases in assessment of local pollution from the coarse CAMS spatial resolution, current methodological approach and main findings may be applicable to sites with similar topographic and atmospheric characteristics, which are still highly based on coal or lignite power plants for electricity generation.

2. Materials and Methods

2.1. Study Area Description and PV System Specifications

Ioannina is a medium-scale urban center with approximately 120,000 residents, located in the region of Epirus, Northwestern Greece. It is situated within an intermontane basin at a mean elevation of 480 m next to Lake Pamvotis, which covers a surface area of 19.4 km², and acts as a continuous source of moisture for the local atmosphere (Figure 1). The city's atmospheric environment is defined by the complex topography. The basin is surrounded by high mountains (1800–2400 m) that severely restrict natural ventilation and the horizontal circulation of air masses [33]. During the winter months, this topography, coupled with low ambient temperatures and high relative humidity, triggers the frequent formation of Cold Air Pools (CAPs) and intense temperature inversions. These inversions act as a stable atmospheric cap, during which the planetary boundary layer (PBL) height does not exceed ~750 m. Especially in Ioannina, LIDAR observations confirm that this exceptionally shallow boundary layer structurally traps fresh biomass burning emissions, creating dense aerosol stratifications, while near surface wind speeds drop to stagnant conditions of less than 1.2 km/h [13]. On the contrary, in summer, the weather conditions are fair and aerosol regime matches the background atmosphere of the Eastern Mediterranean [34].

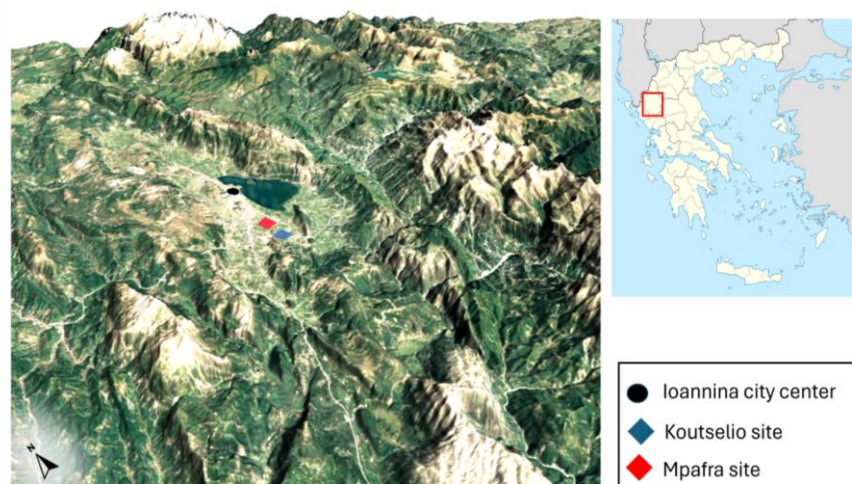


Figure 1. 3D topographical map of the Ioannina basin. The black dot indicates the Ioannina city center next to Lake Pamvotis. The blue and red diamonds represent the locations of the two PV plants evaluated in this study, situated in Koutselio and Mpaфра, respectively. The red box in the inset map indicates the location of the broader study area within Greece.

This study examines two medium-scale PV plants, each with an installed capacity of approximately 100 kWp (99.83 kWp for the Koutselio site and 99.90 kWp for Mpaфра). Both facilities are located within the Ioannina Basin at an elevation of roughly 460 m. Mpaфра is situated into the urban fabric area (8 km south from city center), while Koutselio is located 10 km outside the city center, in a predominantly rural plain area (Figures 1 and 2). Despite the surrounding mountainous terrain, both sites are characterized by absence of significant horizon obstacles. This unhindered view ensures that any variations in power generation are dictated by atmospheric radiative forcing and panel geometry, rather than localized shading.

Both installations utilize crystalline silicon (c-Si) technology with a fixed tilt, though their distinct mounting strategies provide different microclimatic exposures. Specifically, Koutselio is a ground-based facility operating at a 33° tilt and a 190° azimuth, whereas Mpaфра is a rooftop installation utilizing a 15° tilt and a 198° azimuth.

These plants operate as part of a local collective net-billing scheme [35] and their primary function in the context of this study is to serve as ground-truth irradiance integrators. Given the basin's susceptibility to severe, BB-induced winter smog, these installations provide a unique opportunity to evaluate the actual reliability of solar energy assessment under highly polluted, stable atmospheric conditions.



Figure 2. Koutselio ground-based (a) and Mpaфра rooftop (b) PV installations (99.83 kWp and 99.90 kWp, respectively).

2.2. Data Sources and Quality Control

Real energy production data from both parks at a high temporal resolution of 15 min serve as the baseline ground truth measurements in this study. In addition, air quality variables were obtained from the Copernicus Atmosphere Monitoring Service (CAMS), which include detailing Aerosol Optical Depth (AOD) at 550 nm (Total, Dust, Black Carbon, Sulphates), as well as fine and coarse particulate matter concentrations (PM_{2.5} and PM₁₀). Meteorological variables regarding wind components, temperature and humidity were also retrieved from CAMS [36,37]. Furthermore, actual and pristine clear-sky irradiance data were downloaded from the SoDa pro CAMS radiation service [38]. The spatial resolution of the CAMS data is approximately 80 km, centered over Ioannina City, while the temporal resolution is 3 h. Ground-based energy and CAMS data cover the whole year of 2024. All heterogeneous datasets were synchronized into a unified 15-min framework, and statistical quality control was applied to the production logs to eliminate outliers, logging errors, and anomalous daytime zero-generation events.

2.3. Radiative Transfer Modeling and Atmospheric Classification

The libRadtran Radiative Transfer Model (RTM) was utilized to simulate high spectral resolution (at 1 nm) pristine and aerosol-loaded spectral irradiance, by incorporating total AOD as an input variable [39,40]. These simulations were essential for extracting specific spectral signatures and studying the scattering and absorption attenuation mechanisms during dust loading and haze events. Radiative Transfer simulations were executed using the uvspec model, specifically utilizing the DISORT solver running with 6 streams. A constant surface albedo of 0.20 was applied across all runs, acting as a representative baseline for the mixed local topography. The simulations spanned the broadband spectral range from 260 to 2601 nm, employing the Kurucz extraterrestrial solar spectrum and the SBDART correlated-k distribution for gas absorption [41]. To accurately represent the local climatology of Northwestern Greece, the Mid-latitude Winter and Summer atmospheric profiles were selected as the baseline. Solar geometry parameters, including the solar zenith angle, were calculated using standard astronomical algorithms and ingested into the model. The primary outputs of these simulations were the Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI), from which the Beam Horizontal Irradiance (BHI) was directly derived. For the continuous baseline simulations across the entire study period, AOD at 550 nm was dynamically updated via CAMS, while SSA and the Ångström exponent (α) were set to constant regional background values of 0.90 and 1.3, respectively. However, to accurately retrieve the distinct spectral signatures during extreme atmospheric events (Section 3.3), these optical properties were explicitly modified in the event-specific simulations. Specifically, during winter haze episodes, α was increased and SSA was lowered (1.6 and 0.85, respectively) to represent the highly absorbing, fine-mode carbonaceous particles [34]. Conversely, during Saharan dust events, α was significantly reduced (0.3) to properly model the scattering dominance of coarse-mode mineral dust and SSA was raised (0.95). This methodological adjustment ensures high fidelity in replicating the spectral attenuation mechanisms observed under distinct atmospheric forcings.

Following the data synchronization, each timestep underwent two classification processes to isolate and categorize the atmospheric forcing: (i) the modification factor classification and (ii) the aerosol type classification. First, to quantify the solar attenuation magnitude, the Cloud Modification Factor (CMF) and the Aerosol Modification Factor (AMF) are defined as:

$$\text{CMF} = \frac{\text{GHI}}{\text{GHI}_0} \text{ and } \text{AMF} = \frac{\text{GHI}_0}{\text{GHI}_{00}}, \quad (1)$$

where GHI refers to the Global Horizontal Irradiance, under real sky conditions, GHI_0 under clean sky conditions (no aerosols), and GHI_{00} under clear and clean sky conditions (without aerosols and clouds). The CMF classification was based exclusively on soda pro data, while AMF classification utilized libRadtran simulations. Class 1 corresponds to clear and clean sky conditions and Class 5 to overcast and severe air pollution for CMF and AMF, respectively [42].

In the second stage, to classify the timesteps based on the prevailing aerosol type, specific physical and chemical ratios were assessed. These include the Dust Ratio (Dust AOD/Total AOD), the Anthropogenic Ratio [(Black Carbon AOD + Sulphate AOD)/Total AOD] and the Fine Particulate Fraction ($PM_{2.5}/PM_{10}$), all obtained from CAMS reanalysis datasets. After removing all nighttime timesteps, and timesteps that have been already characterized by a CMF class greater than 1, all ratios were combined and specific meteorological thresholds were empirically defined for the purpose of this study. Each timestep was characterized as Dust, Haze Day and Mixed. The “Mixed” category corresponds to timesteps that do not strictly meet the threshold criteria for either haze or dust classifications. A summary of the specific threshold criteria applied for each aerosol category is presented in Table 1. These AOD and PM data correspond to CAMS retrievals on a 3-h resolution and are used here to classify the whole dataset into specific classes (atmospheric conditions) like clean, dust and haze days, while the cloudy days (CMF above 1) correspond to another category. From the whole dataset during the year 2024, approximately 53.5–54.2% of the observations were characterized as cloudy conditions, 25.2–25.7% as clean sky, 13.9–14.0% as mixed atmospheric conditions, 5.1–5.3% as Saharan dust events, and 1.5–1.7% as localized winter haze.

To justify and validate the threshold criteria (Table 1), an empirical tuning approach was conducted using independent ground-based measurements from the Ioannina city center station. Specifically, the haze thresholds were adjusted so that the identified events coincided with periods of elevated ground-level $PM_{2.5}$, NO_2 and SO_2 concentrations, which are characteristic of local biomass burning [14,34]. Similarly, dust thresholds were calibrated to align with elevated ($>30 \mu g m^{-3}$) ground PM_{10} records. This cross-examination serves as an empirical sensitivity test, ensuring that the selected thresholds capture true local atmospheric events, despite the coarse resolution of the reanalysis product. It should be noted that current study does not aim to provide a detailed aerosol classification in the Ioannina Basin, but to roughly detect separate episodes of Saharan dust and local haze/smog conditions, to evaluate their impacts on solar radiation attenuation and PV power loss.

Table 1. Proposed threshold criteria for aerosol type classification applied in this study.

Class	AOD	Ratios	PM Fraction
Haze	$AOD > 0.15$	Anthr. Ratio > 0.5 , Dust Ratio < 0.25	> 0.65
Dust	$AOD > 0.15$	Dust Ratio > 0.4	< 0.75
Clean	$AOD \leq 0.15$	-	-

Before proceeding with DT’s performance, the real impact of atmospheric forcing on energy production was evaluated by comparing the generation logs of the PV plants against the theoretical solar energy production for clear and clean skies (CMF = 1 and AMF = 1, respectively). This methodological approach gives emphasis to the specific hours, on which each event occurs, for example winter morning and early afternoon for haze events, ensuring a fair and a solar geometry independent comparison.

2.4. The Digital Twin Framework

A DT framework was developed to simulate the expected power output of the PV plants. Conceived as a site-specific diagnostic and attribution, this framework is designed to isolate and quantify the exact impacts of localized atmospheric forcing on PV performance. The model first integrates topographical and solar geometry characteristics by calculating precise solar positions (zenith and azimuth angles) using the pvlib library combined with a customized horizon mask that was derived from PVGIS for each site [43,44]. Even though both sites are characterized by a general unhindered view, located in plain areas, this is crucial for intermontane basins, as it filters errors that could be derived from the surrounding mountain ridges. Subsequently, the DT converts the GHI and DNI derived from CAMS into Plane of Array (POA) irradiance, tailored to fit the fixed tilt and azimuth of each installation. A dynamic thermal loss factor was also implemented, since PV plants lose approximately 0.4% of their efficiency for every degree Celsius increase in ambient temperature [22,45].

The DT framework was empirically calibrated using the actual power production data exclusively during timesteps classified as having clean and clear sky conditions (CMF = 1, AMF = 1). This baseline calibration effectively isolates the ideal, unattenuated performance curve for each installation. This calibration subset represents approximately 25% of the data. Because the calibration process computes only a single parameter i.e., the baseline median system efficiency, the risk of overfitting is inherently minimized. To ensure a strict and transparent validation strategy, the evaluation metrics (R^2 , MBE, MAE, RMSE) were computed across the entire annual dataset under all operational conditions. Consequently, for the remaining 75% of the dataset (cloudy, dust, haze, and mixed conditions), the validation acts as a completely independent test. The efficiency factor was applied across the entire dataset using the GHI product to simulate the generation at any given timestep. By comparing the simulated energy output against actual PV generation, the framework identifies the specific atmospheric conditions under which the model exhibits the largest discrepancies, allowing us to investigate the underlying causes of these biases.

3. Results and Discussion

3.1. Impact of Atmospheric Forcing on Real Energy Production

To quantify the relative power deviation under different atmospheric forcings, an hour-matched clear sky baseline was established for each site. This baseline represents the expected maximum power generation as it's derived from the real power data of the PV plants during clean and clear hours (CMF = 1 and AMF = 1). The real power production was then compared against this expected profile for strictly identical temporal windows (same month and time of day).

From the evaluation of this comparative framework, some important findings emerged. As expected, clouds are the primary driver of generation deficits [46–48], as under fully overcast skies (CMF = 5), empirical data shows that the mean power production can drop by over 80% for both sites (Figure 3). When isolating clear-sky aerosol loading, Saharan dust causes a consistent energy loss of roughly 14% across both sites. Conversely, the production under local urban haze events reveals stability. When compared strictly to the exact same hours under pristine conditions, Koutselio plant demonstrated a minimal power decrease of just 4.8%, while the Mpaфра rooftop installation recorded a slight increase of 3.2% (Figure 3). However, this minimal positive deviation should be interpreted with caution, as it falls within the combined margin of uncertainty stemming from the coarse resolution of CAMS data, microclimatic variance between the experimental sites and baseline calibration limits, rather than representing a definitive operational surplus. The presence of local smog, composed of biomass-burning aerosols during winter [14,18],

is confined within the lowest boundary layer (usually below 500 m), associated with clean air aloft [13]. This low-level pollution results in lower AOD values in winter (compared to spring and summer) over the region, and less actual (and simulated) attenuation of solar radiation. This is a basic reason that haze events during wintertime ranked third in irradiance attenuation and power loss in the examined PV park. Note also, that the high carbonaceous aerosol loading and the dense haze conditions occur early in the morning and in late evening and night, hours without sunshine in winter, due to residential wood burning emissions [13]. Given the low irradiance and power production data during these time frames, any uncertainty in CAMS data and event classification may affect the results of relative power deviation (Figure 3).

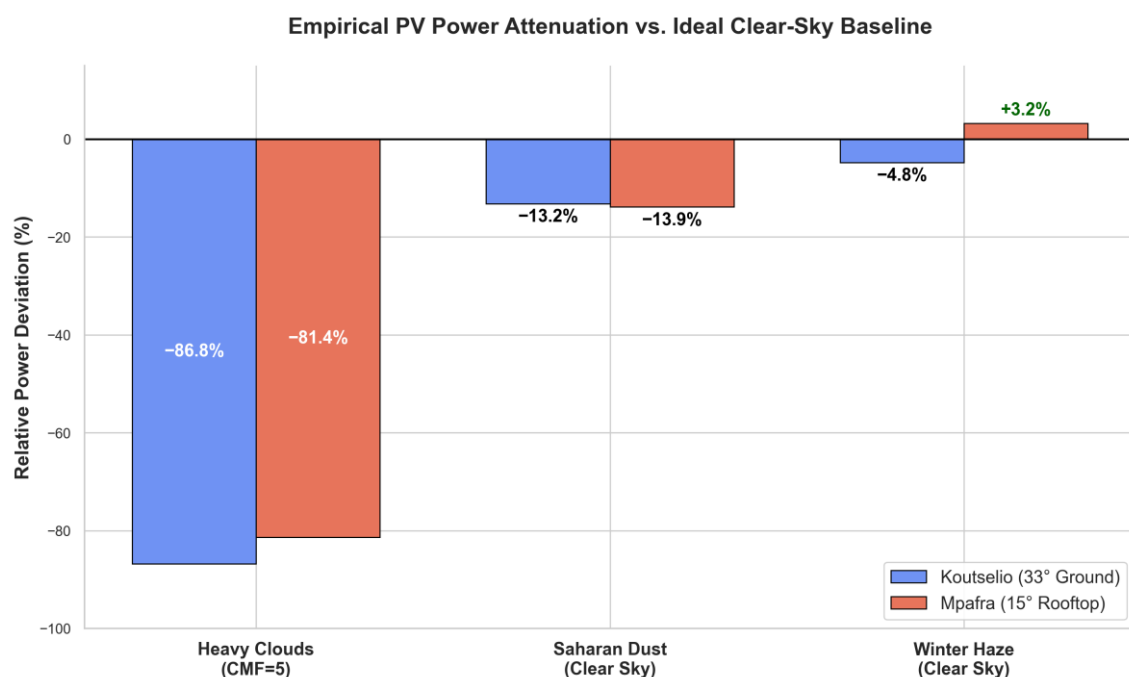


Figure 3. Relative power deviation across Mpaфра (orange) and Koutselio (blue) sites, during over-cast conditions, Saharan dust loadings and winter haze events. The green text indicates a positive power deviation (energy surplus).

To provide a comprehensive overview of the annual generation dynamics, seasonal variability, and diurnal profiles for both PV installations under all weather conditions, detailed production heatmaps and time-series analyses are presented. Figures 4 and 5 provide a broader overview of the empirical solar energy production in the two evaluated PV plants (Koutselio and Mpaфра) over the entire study period (2024). These figures illustrate the solar power generation dynamics for each site using three distinct visualizations: (A) a solar production heatmap detailing the hourly generation intensity across the year, (B) the seasonal average diurnal power profiles, incorporating interquartile ranges (IQR) to highlight the variability related to weather conditions, and (C) the daily total energy yield overlaid with a 7-day rolling average to capture macroscopic seasonal trends. These plots establish the baseline operational behavior of the two distinct installation geometries (ground-based vs. rooftop), against which the specific atmospheric forcing events were evaluated.

From a direct comparison between the sites, the solar power production is higher at Koutselio PV park, maximizing in summer early afternoon hours. Mpaфра shows similar seasonal-average diurnal profiles with reduced power productions, while both PV parks exhibit a similar annual variability in energy yield during 2024 with higher fluctuations

from October to April due to changing weather conditions and extensive cloudiness, while in summer, fair weather drives more standard power generation on daily basis, which is approximately 550–600 kWh in Koutselio and ~500 kWh in Mpaфра.

Solar Production Analysis: Koutselio PV Park(2024)

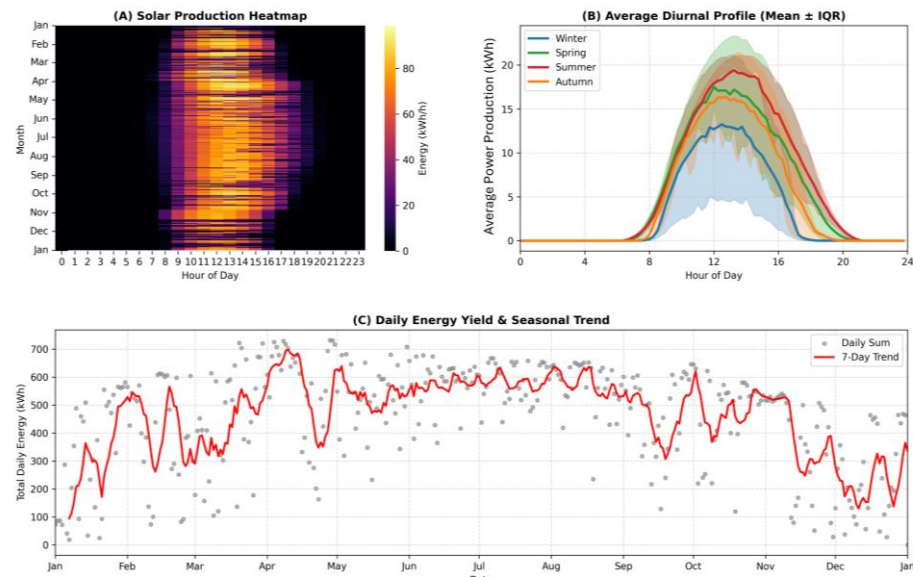


Figure 4. Comprehensive solar production analysis for the Koutselio ground-based PV plant (33° tilt). The panel includes (A) an hourly generation heatmap, (B) seasonal average diurnal profiles (solid lines) with their corresponding interquartile ranges (indicated by the shaded areas for each season) and (C) the daily total energy yield with a 7-day averaging line.

Solar Production Analysis: Mpaфра PV Park(2024)

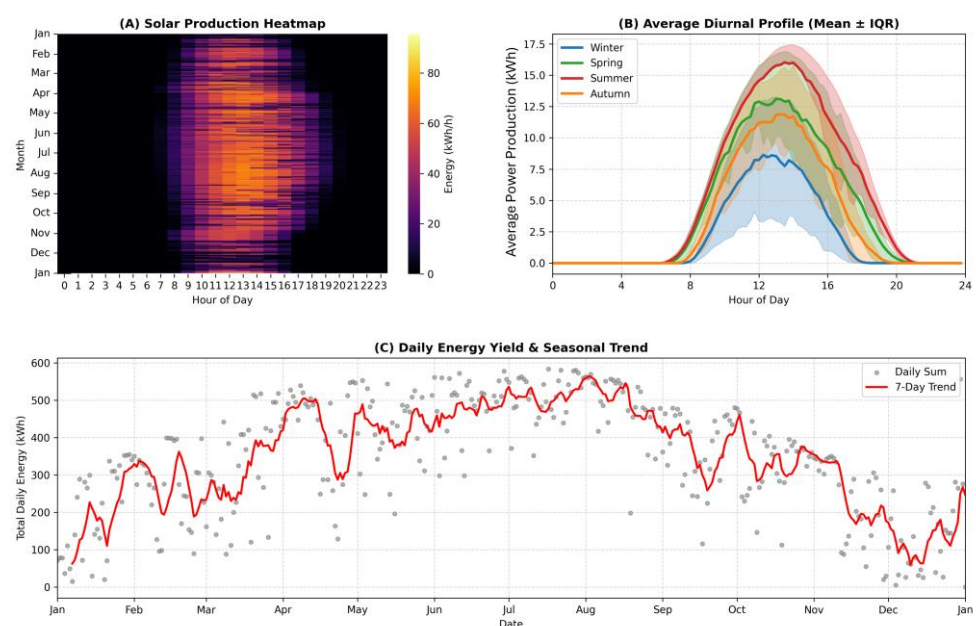


Figure 5. Comprehensive solar production analysis for the Mpaфра rooftop PV plant (15° tilt). The panel includes (A) an hourly generation heatmap, (B) seasonal average diurnal profiles (solid lines) with their corresponding interquartile ranges (indicated by the shaded areas for each season) and (C) the daily total energy yield with a 7-day averaging line.

For a detailed temporal breakdown of the physical and operational dynamics during the severe April 2024 Saharan dust intrusion, as well as a comprehensive top five dust event loss analysis, the reader is referred to Appendix A (Figures A1–A3). Since both sites fall within the same coarse CAMS grid, they share the AOD input (with only negligible interpolation variations), resulting in highly similar simulated irradiance profiles. Consequently, any observed differences in actual PV power generation are strictly driven by their distinct module efficiencies and installation geometries. These results revealed that severe AOD values (0.9–1.2) on specific days may cause an energy loss of ~50–70% in both PV plants, while a moderate dust AOD of 0.4 (common for several dust events in Greece) may result in a 14–18% loss of solar energy production (Figure A1).

3.2. Digital Twin Validation & Baseline Performance

The DT performance demonstrated robust accuracy across both plants. The Coefficient of Determination (R^2) reached 0.847 for Koutselio and 0.865 for Mpaфра, while Mean Bias Error (MBE) was near zero for both sites (−0.008 kWh and −0.139 kWh, respectively), suggesting that the baseline calibration against the real production data during clean and clear sky conditions successfully eliminated systematic bias, providing a reliable reference. Furthermore, the Mean Absolute Error (MAE) remained consistently low (1.69 kWh for Koutselio and 1.28 kWh for Mpaфра), while Root Mean Square Error (RMSE) reached 2.82 kWh and 2.00 kWh, respectively. The slightly higher absolute error magnitude for Koutselio is likely linked to its higher efficiency (24% for Koutselio and 18% for Mpaфра) and overall greater energy production.

For the sake of brevity and clarity, the plots of the DT visual validation are presented for the Koutselio PV plant, since equivalent behavioral trends were observed for Mpaфра installation. In this respect, the scatter plot in Figure 6a reveals an even error distribution across seasons. The best relative performance was observed in summer (MAE: 1.30 kWh, RMSE: 2.23 kWh, MAPE: 21.9%), while significantly greater relative biases occurred in winter, predominantly associated with lower sun elevations, the overall reduced absolute power generation and cloud cover (MAE: 2.00 kWh, RMSE: 3.17 kWh, MAPE: 57.5%). This indicates that the implemented thermal loss factor and geometric models successfully capture the baseline PV performance across varying temperature profiles, atmospheric and meteorological conditions, since summer is characterized by significantly lower PM and carbonaceous aerosol concentrations and absence of BB emissions [49]. Furthermore, the hourly MAE analysis demonstrates that while the absolute error naturally scales with total solar irradiance, peaking (MAE = 2.2 kWh) around local noon (Figure 6b), the model exhibited higher relative deviations during the early morning hours due to low solar energy. This specific diurnal error pattern is linked to the complex micrometeorology of the local topography, and more particularly to the formation of shallow CAPs within the basin, the effects of which on solar energy production will be comprehensively analyzed.

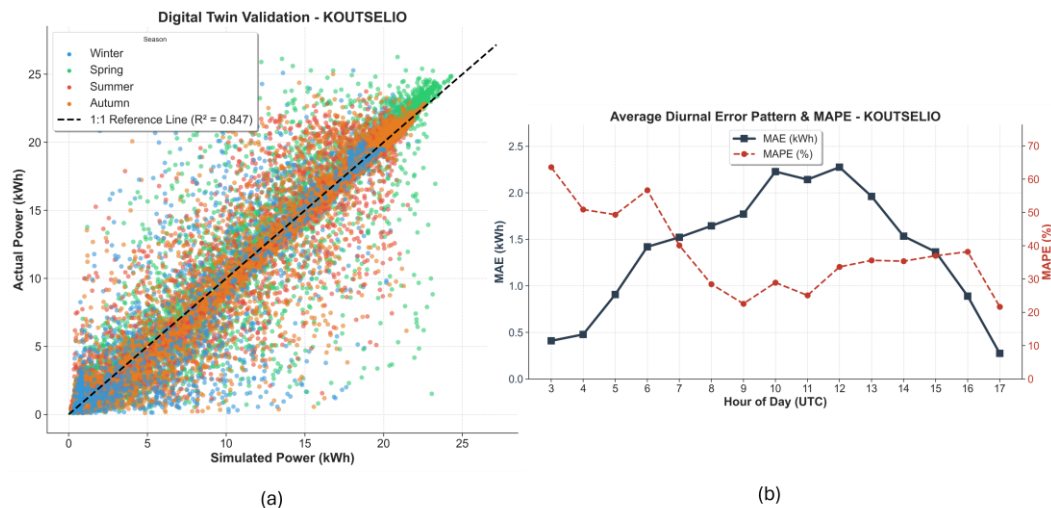


Figure 6. Validation of the DT's performance for the Koutselio PV plant. (a) Scatter plot of simulated versus actual power across different seasons. (b) Mean diurnal distribution of MAE (blue) and MAPE (red) from the comparison between real and simulated power.

On the other hand, the impact of clouds on DT's performance is of high importance, since it could be especially high resulting in significant discrepancies between actual and simulated power generation. As shown in the scatter plot (Figure 7a), the model achieves its highest accuracy under clear skies ($R^2 = 0.95$), with the performance progressively decreasing as cloud cover increases, dropping to $R^2 = 0.24$ under fully overcast conditions. The error distribution boxplot (Figure 7b) reveals that the maximum error dispersion occurs under scattered clouds. As is widely documented in solar forecasting literature, this dispersion is driven by the inherent unpredictability of partial cloud cover, where rapid irradiance fluctuations and over-irradiance caused by cloud-edge enhancements, lead actual PV generation to momentarily exceed clear-sky expectations [23,50,51]. Furthermore, this sub-pixel cloud variability poses a significant challenge for broadband satellite and reanalysis models like the CAMS radiation product. Low resolution gridded satellite inputs systematically fail to capture highly localized shading anomalies and rapid variations in solar irradiance, thereby inflating the simulation error [29,50,52]. Conversely, under fully overcast skies, the error dispersion narrows again due to the consistent, low irradiance conditions and small fluctuations in solar energy.

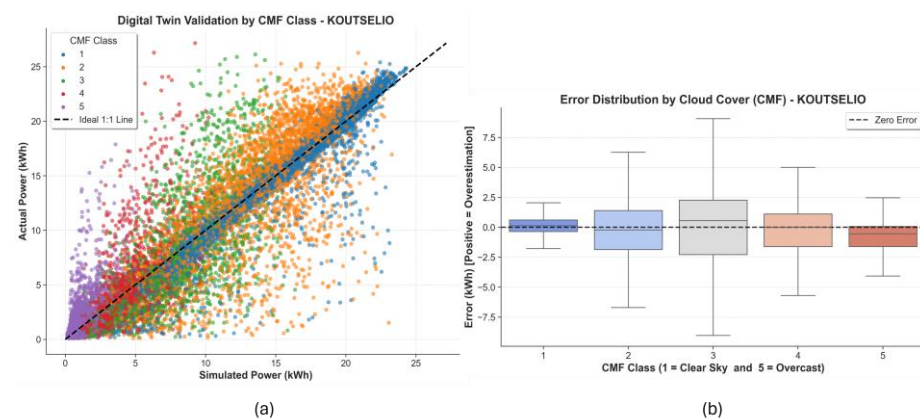


Figure 7. Impact of clouds on DT's accuracy. (a) Scatter plot of simulated versus actual power across varying CMF classes, (b) boxplot of absolute simulation errors across CMF classes, highlighting maximum error dispersion during intermediate scattered cloud conditions (CMF = 3) due to sub-pixel cloud variability.

pixel variability and cloud-edge enhancements. Different colors correspond to distinct atmospheric conditions.

Regarding DT's performance across various aerosol types, the analysis revealed that the model exhibits various behaviors that are linked to the intensity of the aerosol loading, as well as the physical properties of aerosols (Figure 8). As shown in the error distribution box plot (Figure 8a), the DT maintains a relatively low and stable error profile under pristine conditions and Saharan dust events (averaging $R^2 = 0.96$ and MAE = 0.77 kWh for both conditions). However, localized urban haze introduces an error dispersion that drops the model's performance to $R^2 = 0.88$, while the MAE reaches 1.83 kWh, twice that of the previous cases, indicating systematic overestimation of simulated solar power. This indicates that the simulation of urban pollution, mainly consisted by carbonaceous absorbing aerosols like BC and BrC [49] at the lower (<500 m) atmospheric levels, is highly uncertain by the models and CAMS reanalysis that use coarser spatial resolution and emission inventories that fail to detect and accurately represent local haze events. The Kernel Density Estimation (KDE) plot (Figure 8b) demonstrates that as the overall aerosol concentration (AMF) increases, the simulation error distribution systematically shifts from zero towards positive values, revealing a consistent overestimation of solar power, still maintaining a normal leptokurtic distribution, indicating that during heavy aerosol loading (AMF 3), the model's positive bias is highly concentrated and systematic. This uncertainty occurs because high aerosol loading severely attenuates the direct solar beam, making satellite retrieval algorithms hypersensitive to predefined aerosol microphysical assumptions, such as the SSA and α , which play a very important role in aerosol attenuation and the spectral distribution of the diffuse radiation [53]. As a result, difficulties in representing local aerosol conditions, such as winter smog and fog, and the absorbing properties of BC and BrC, become more pronounced under high atmospheric loads, causing significant deviations in energy production forecasting [54,55].

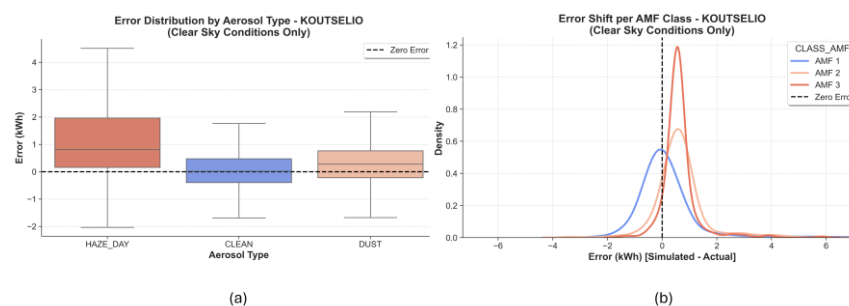


Figure 8. Impact of clear-sky aerosol forcing on the DT simulation error at Koutselio PV plant. (a) Error distribution boxplot across different aerosol type classifications, (b) Error Shift across various aerosol intensity classes (AMF).

The statistical summary also reveals a Mean Absolute Percentage Error (MAPE) of 88.3% and a positive MBE of 1.55 kWh during haze events (compared to 14% and 0.37 kWh, respectively, during dust events). This overestimation is largely driven by the moment of the day these events occur. As winter smog is trapped within shallow CAPs during early morning and late afternoon hours, the actual PV generation remains at its lowest levels. In such cases, even minor absolute prediction errors (small MAE) are mathematically amplified into massive percentage deviations (inflated MAPE) due to the small denominator effect.

This overestimation during haze events, confirms that standard satellite-based models are largely “blind” to localized, low level atmospheric phenomena [56–58]. In fact, even ground-based measurements of fine particulate matter in the Ioannina Basin are highly

susceptible to significant biases induced by high relative humidity levels and frequent winter fogs, which alter the scattering properties of the aerosols [33]. Furthermore, Paraskevopoulou et al. [49] revealed highly variable light-absorption by BC and BrC in Ioannina, strongly dependent on intensity of wood burning emissions and local meteorology during winter. Similarly, when testing advanced atmospheric models over the same basin, researchers found that macro-scale systems consistently fail to capture wintertime pollution because they cannot properly resolve the complex mixing processes of the local PBL over these topographies [59]. Consequently, the micro-scale attenuation caused by radiation fog is merely missed by the satellite inputs leading the DT to falsely simulate higher power generation.

3.3. Physical Drivers of Error Asymmetry in PV Modeling

As discussed above, satellite-driven reanalysis models with coarse spatial resolution (e.g., CAMS at ~80 km) often struggle to resolve highly localized winter haze, making the integration of in-situ power generation data essential to evaluate the real impact of these events on PV production. Figure 9 illustrates the average diurnal profiles of power generation (kW) at the Koutselio and Mpafra sites under winter haze (Figure 9a) and Saharan dust (Figure 9b) conditions. To quantify the aerosol-induced attenuation, the measured performance is evaluated against two modeling levels: (i) the theoretical Pristine Sky production calculated by using libRadtran simulations under zero aerosol conditions, and (ii) the Clean Sky baseline, which represents the empirical average of measured power during clean and clear days ($AMF = 1$, $CMF = 1$), matched for the same months and hours as the target episodes. It is observed that Mpafra consistently exhibits lower absolute power levels than Koutselio, a result of its lower efficiency as a roof installation (24% for Koutselio and 18% for Mpafra).

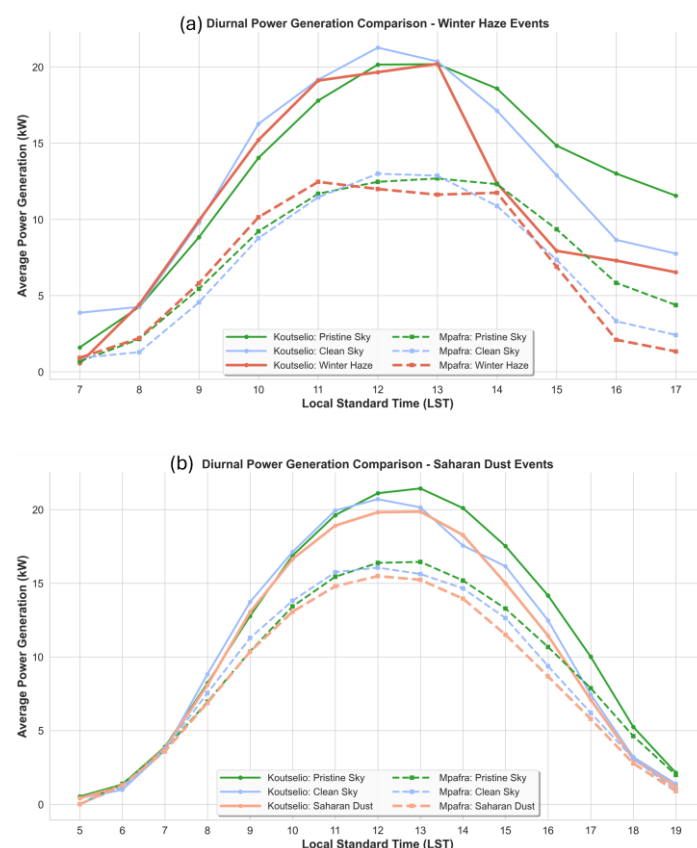


Figure 9. Mean diurnal variation of average power generation (kW) for the Koutselio (ground-based) and Mpafra (rooftop) PV plants during (a) winter haze and (b) Saharan dust events. The plot

compares the simulated Pristine Sky (theoretical maximum), modeled via libRadtran (green) the PV Digital Twin under zero-aerosol conditions, the Clean Sky (empirical baseline; blue), representing the average measured power during clean and clear sky for the same months and hours, and the measured power during the specific aerosol episodes (orange).

Regarding the specific aerosol impacts, Saharan dust events (Figure 9b) cause a notable power reduction across the diurnal cycle, reaching average daily decreases of 5.9% and 3.5%, when compared to the clean-sky baseline, at the Koutselio and Mpaфра sites, respectively. The most pronounced deficit is detected around local noon and afternoon hours. This dust-related reduction in solar power generation could be considered important, since the Ioannina Basin is generally less affected by intense dust events compared to southern and central Greece [60].

Conversely, during winter haze events (Figure 9a), the power deficit exhibits a distinct diurnal asymmetry. Higher decreases in power generation, in the order of 6% (Mpaфра) to 19% (Koutselio), are detected during the early afternoon hours at both sites. This is attributed to the rapid increase in local haze and carbonaceous aerosol concentrations during the afternoon, driven by a lowering mixing layer and the activation of residential fireplaces and woodstoves [34]. However, some discrepancies occur during the morning hours, as the power production closely tracks and occasionally exceeds the clean-sky conditions, while at midday it stays closer to pristine conditions. This morning over-performance is likely a synergistic result of multiple environmental and technical factors. Geometrically, the lower tilt angle of the rooftop installation provides a larger sky-view factor (SVF), which enhances the capture of isotropic diffuse radiation that prevails during haze events [61]. Concurrently, this optical effect operates in tandem with the enhanced electrical efficiency of the modules during early morning hours, driven by the characteristically low ambient temperatures. However, this trend must be treated as an empirical indication rather than a robust geometric benefit, as it remains inherently coupled with potential event misclassification anomalies arising from the coarse spatial resolution of CAMS inputs, which partly explains the minimal overall winter energy impact recorded for both sites, as detailed in Section 3.1. To sum up, this slight positive deviation during haze events (morning hours; Figure 9a) may arise from several reasons including diffuse-light capture, lower module temperature, local cloud/fog effects, event misclassification, or baseline uncertainty.

Furthermore, this modest cumulative energy impact is inherently linked to the specific photovoltaic technology deployed at both sites. Both installations utilize standard c-Si modules, which exhibit a higher spectral resilience to urban haze compared to wider-bandgap technologies. Peters et al. [7] demonstrated that while urban fine-mode aerosols strongly filter out blue light, c-Si cells can still utilize the less affected red and near-infrared bands for power production. This spectral adaptability effectively compensates for the expected drop in power output. Especially for Ioannina Basin, the large BC and BrC concentrations during wintertime cause a significant absorption of solar radiation, particularly at short wavelengths, due to strong BrC absorption in UV and near-VIS [34,49]. However, the absorption of solar light at longer (>500 nm) wavelengths was found to be significantly lower, thus allowing solar radiation reaching the ground and power generation at red and infrared bands [49,7].

Overall, the diurnal variation of the haze curve production is driven by three primary factors: First, the high morning relative humidity across the basin drives the hygroscopic growth of aged aerosols from the previous night [34]. This physical transformation enhances their light scattering efficiency [62], increasing the SSA values and shifts the optical behavior toward forward scattering, which in turn, elevates the diffuse irradiance reaching the modules. Along with PV temperature being low during early morning hours, the

modules operate at peak electrical efficiency partly offsetting the irradiance attenuation. Secondly, in late afternoon hours, residents start biomass heating that releases fresh highly absorbing BC. As the boundary layer starts to collapse due to thermal inversions, these pollutants are trapped near the surface blocking direct irradiance. Finally, winter smog in the Ioannina Basin is a morning and late-afternoon phenomenon, so the statistical sample for midday haze events is virtually nonexistent throughout the entire winter season. Consequently, this results in the slight midday dip observed in the generation curve, while some discrepancies may be also statistical artifacts due to data scarcity (Figure 9).

To validate how these distinct aerosol types interact with the c-Si technology across the solar spectrum, the spectral and the percentage spectral irradiance attenuation during a haze and a dust event were analyzed in Figure 10 through libRadtran simulations. The examined dust event corresponds on 15 April 2024, a day with intense dust loading ($AOD_{550} = 1.2$), while the current simulations are at 12:00 UTC. The simulations on the haze day are at 8:00 UTC on 12 January 2024, characterized by moderate columnar AOD_{550} of 0.35. For both cases, the whole process and the aerosol optical properties implemented as inputs in libRadtran model were fully described in Section 2.3.

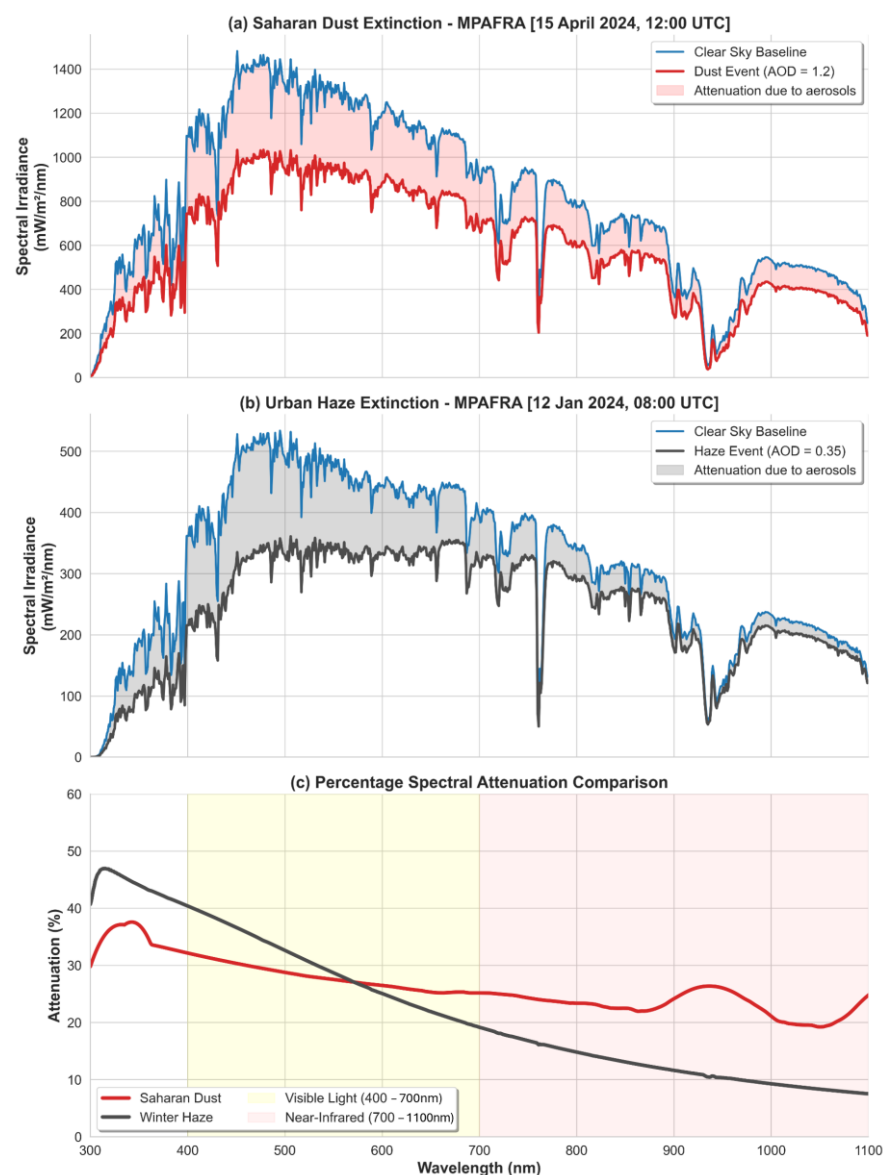


Figure 10. Spectral analysis of solar irradiance attenuation during (a) a severe Saharan dust event (15 April 2024 at 12:00 UTC, $AOD = 1.15$) demonstrating broadband attenuation, (b) a local winter

haze event (12 January 2024 at 8:00 UTC, AOD = 0.35), indicating selective filtering primarily within the UV and visible spectrum. (c) Percentage spectral attenuation of solar irradiance in the two days with respect to theoretical clean conditions.

The spectral attenuation caused by the dust event, indicated by the shaded area at Figure 10a, demonstrates a broadband attenuation across the entire spectrum, reaching 38% at 300 nm. Because Saharan dust particles are coarse, they scatter incoming sunlight in all directions (Mie scattering). While a subtle “red shift” is theoretically present due to the specific scattering processes and mineralogical composition of dust (e.g., iron oxides such as hematite are absorbing at shorter wavelengths; [63]) and faintly visible in the slight downward slope of the spectral attenuation curve (Figure 10c), the dominant physical mechanism observed here is the sheer broadband optical blocking [64]. Therefore, coarse dust particles attenuate the solar radiation at all wavelengths, i.e., about 35% at UV (300–400 nm) and ~20–25% in the infrared (>800 nm). This attenuation can reduce direct solar radiation (DNI) by up to 90%, forcing the fixed-tilt PV panels to rely mostly on the diffused light, which significantly lowers their energy yield [65,66].

While crystalline silicon (c-Si) PV technology exhibits a broad spectral response that peaks in the near-infrared, it relies heavily on the highly energy-dense visible band of the solar spectrum to generate the bulk of its photocurrent [67]. Consequently, heavy dust loading effectively “blinds” the modules during peak theoretical solar radiation and power generation hours, accounting for the significant daily energy deficits during dust events (~13%) quantified in Section 3.1.

Unlike the broadband spectral attenuation caused by coarse dust particles, the signature of the winter smoke/haze event reveals a selective wavelength filtering process (Figure 10b). The attenuation of solar irradiance is not symmetric across the spectrum, with a significantly larger decrease in the UV region that progressively lowers with increasing wavelength. This is further validated by the percentage attenuation comparison in Figure 10c, where the haze profile exhibits a steep wavelength decline. The high concentrations of PM_{2.5} and carbonaceous aerosols heavily attenuate solar irradiance at shorter wavelengths and in the visible spectrum (300–600 nm) through strong scattering and absorbing processes reaching approximately 45% of irradiance attenuation. This spectral behavior is consistent with high BrC absorption at shorter wavelengths, leading to more spectral selective attenuation of urban aerosols [68].

However, the spectral difference between the pristine clear-sky curve and the haze curve narrows significantly in the longer wavelengths (red and near-infrared regions, >700 nm). As shown in Figure 10c, the percentage attenuation drops sharply below 10–15% in the near-infrared spectrum. Fine aerosols are physically small to effectively block these longer wavelengths, allowing a substantial portion of the near-infrared irradiance to penetrate the boundary layer and reach the surface. This spectral behavior corroborates the system’s operational resilience: despite the intense visible attenuation, the c-Si modules successfully convert the penetrating near-infrared photons into energy. Therefore, the winter haze in the Ioannina Basin, although may result in significant UV-absorbing processes modulating the photochemical reactions in the atmosphere [49], they affect less the whole solar spectrum and the power generation. Furthermore, recent winter research campaign showed that this haze layer is detected at the lowest boundary layer (approximately ~500–600 m) with clean atmospheres above [12]. On the contrary, intense dust events are vertically distributed at higher atmospheric levels, leading to significantly larger columnar AOD and irradiance attenuation [69].

However, this spectral behavior is further contextualized by a significant discrepancy between model-derived and ground-based air quality metrics. During the most intense haze episode on 12th of January, the CAMS reanalysis product reported a maximum

AOD₅₅₀ of 0.35, with PM_{2.5} concentrations estimated at 17 µg/m³. In contrast, local ground-based sensors recorded PM_{2.5} concentrations up to 31 µg/m³ during the same hour. Because the coarse CAMS spatial grid covers the entire basin, it essentially averages out these localized emission peaks. While stable winter air masses create a relatively uniform pollution layer over the broader valley, affecting the PV sites as well, the highest aerosol concentrations naturally occur at the urban core. This comparison clearly highlights how low-resolution reanalysis products tend to underestimate intense, localized urban pollution [70,71]. As demonstrated by Marchand et al. [29], satellite-derived databases like CAMS often struggle to provide accurate irradiance data in regions with complex topography and higher altitudes. Furthermore, the large satellite pixels lead to spatially averaged atmospheric conditions [28], mathematically preventing these regional models from resolving the intense aerosol optical thickness concentrated within narrow urban valleys. This is especially important in Ioannina, where the high carbonaceous aerosol concentrations are detected at lower heights over the basin, while the regional mountainous terrain is relatively clean due to forested areas and absence of sources. Consequently, the actual AOD during winter inversions may be substantially higher than satellite estimates suggest. To overcome these limitations, recent methodological shifts emphasize the use of ground-based spectral irradiance to precisely retrieve aerosol optical properties in complex Greek mountainous environments [32]. This intense, undetected local smog further amplifies the selective scattering and absorption at shorter wavelengths, underscoring its defining role in PV efficiency variations in the Ioannina Basin, contributing to enhanced biases in simulating solar spectrum variations and the amount of power generation. Under these environmental conditions, more detailed and accurate representation of aerosol optical properties is needed to assess the scattering and absorption processes and accurately simulate solar energy potential. The results of recent winter campaigns focusing on carbonaceous aerosol optical and chemical properties [12,34,49], may be useful for establishing the representative winter aerosol baseline over the Ioannina Basin, that could be used in radiative transfer models for more reliable simulations of energy potential in future studies. On the other hand, continuous recordings of solar power generation under varying atmospheric conditions, the use of smart meters and machine learning models for assessment of the non-linear association between energy potential and atmospheric conditions, could be helpful in simulation, near-time forecasting, and enhancing the efficiency of power generation [72–75].

3.4. Framework Uncertainties and Methodological Limitations

To assess the diagnostic findings, several methodological uncertainties inherent to the modeling framework must be acknowledged. Primarily, the coarse spatial resolution (~80 km) and the temporal interpolation of CAMS data (from 3-h to 15-min intervals) limit the precise representation of rapid, micro-scale atmospheric dynamics in topographically complex basins [34]. Additionally, the libRadtran simulations rely on a generalized constant surface albedo (0.20) and fixed background aerosol optical properties (e.g., SSA and Ångström exponent), which may not perfectly capture continuous localized fluctuations in aerosol composition. For instance, the model's fixed SSA does not account for the hygroscopic growth of carbonaceous particles during high-humidity winter mornings [34]. While this limitation contributes a minor fraction to the observed morning GHI simulation discrepancies, future iterations of the DT aim to integrate relative humidity parameterizations for dynamic SSA adjustments. Furthermore, the DT utilizes a standard deterministic thermal loss factor (−0.4%/°C) based on ambient conditions rather than in-situ module glass temperature measurements, while minor statistical discrepancies may also arise from inherent noise or maintenance gaps in the PV inverter production logs. Despite these constraints, anchoring the diagnostic framework to real, in-situ pristine-sky operational

baselines effectively mitigates these uncertainties, allowing for a robust isolation of the core atmospheric impacts.

4. Conclusions

This study aimed to quantify the impact of specific atmospheric aerosol events—namely Saharan dust intrusions and localized winter haze—on solar energy production, and to investigate the distinct optical behaviors and attenuation mechanisms of each aerosol type within the complex, topographically enclosed basin of Ioannina, Greece. Given the region's vulnerability to dense winter smog driven by residential wood combustion, establishing a reliable assessment of PV resilience under such conditions is critical for local energy planning.

The key findings of this study provided a comprehensive understanding of how localized atmospheric forcing dictates photovoltaic performance in complex intermontane terrains, with intense localized emissions during wintertime. By integrating Digital Twin (DT) modeling with empirical data, the operational impact of winter haze and Saharan dust was isolated and quantified. The framework demonstrated high accuracy, achieving an R^2 of 0.847 for the ground-based plant (Koutselio) and 0.865 for the rooftop installation (Mpaфра). Crucially, the comparison between real and simulated energy outputs revealed an operational resilience of PV systems during winter smog events. LibRadtran simulations revealed that while Saharan dust intrusions act as a broadband optical barrier causing irradiance attenuation across all wavelengths, winter haze episodes composed by high amounts of carbonaceous absorbing aerosols (black and brown carbon), primarily act as a selective filter, with higher solar attenuation in the UV and near-visible spectrum. Because c-Si PV arrays maintain high conversion efficiencies in penetrating near-infrared spectrum and benefit from the low ambient temperatures associated with Cold Air Pools in the region, the overall energy loss remains minimal during winter haze conditions. However, the loss of power generation under haze episodes may be underestimated by using coarse resolution CAMS data, since localized near-surface atmospheric pollution layer seems to be more intense than that simulated from satellite and reanalysis datasets. Installation geometry further dictates this vulnerability: the ground-based setup (33° tilt) experienced a minor power deviation of −4.8% during intense haze, whereas the low-tilt rooftop geometry (15°) leveraged a higher SVF to capture scattered diffuse irradiance, ultimately achieving a +3.2% energy surplus.

While the DT methodology provides reliable estimates of energy yields, a main limitation of this study is the reliance on low-resolution reanalysis products over complex terrains. Since regional models struggle to capture micro-scale pollution trapped inside narrow valleys, simulation discrepancies persist, leading to potential event misclassification. Furthermore, the inherently small statistical sample size of midday winter haze events restricts the absolute certainty of some temporal generation patterns, meaning these specific hypotheses should be treated as empirical indications rather than universally robust findings. From a practical perspective, the minimal smog-related energy losses at the suburban Mpaфра and Koutselio sites (8–10 km from the city center) indicate that cloud cover and Saharan dust dominate short-term grid dispatching in these peripheral areas. This highlights the strategic value of deploying networks of low-cost particulate sensors directly on PV sites, rather than relying on coarse satellite data or expensive reference-grade equipment. For intra-urban rooftop PVs, larger pollution levels could cause higher energy penalties that compound winter cloudiness. Therefore, leveraging low-cost, high-resolution localized monitoring remains essential for future research aiming to deploy this DT framework for decentralized energy communities in heavily polluted urban environments.

From a socio-environmental perspective, these results reshape the prevailing discourse on solar energy potential in mountainous regions. The proven resilience of solar output during severe haze events suggests that decentralized solar-driven electrification (e.g., through residential heat pumps) can serve as a practical solution to break the regional dependency on biomass combustion, which is the primary driver of winter smog in Ioannina. Furthermore, this operational stability underscores the immense potential of empowering local RECs integrated within the urban and suburban fabric. The successful transition towards such decentralized models relies inherently on the implementation of smart grid technologies. By leveraging advanced forecasting and real-time monitoring, smart grids can efficiently balance the highly localized and variable rooftop solar generation with flexible electrification loads. Overall, while these empirical findings provide a strong indication of c-Si PV resilience under localized winter smog, their generalizability to other polluted intermontane valleys should be approached with caution and verified through further comparative evidence. Methodologically, the DT framework is highly scalable to regions with varying topographies and aerosol profiles (e.g., coal combustion). Transferring this parameterized tool simply requires updating geospatial inputs and local aerosol optical properties (such as SSA, α and AOD), followed by a site-specific clear-sky calibration to establish the unique operational baseline of the new PV plant. Nevertheless, the successful integration of localized, small-scale PV networks emerges as a highly promising strategy for similar mountainous regions. Prioritizing PV installations on rooftops and within already developed peri-urban areas provides a practical pathway to alleviate regional energy poverty. Importantly, this approach minimizes the need to develop pristine mountainous landscapes, thus balancing renewable energy expansion with environmental and landscape conservation.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are in this manuscript:

α	Ångström Exponent
AMF	Aerosol Modification Factor
AOD	Aerosol Optical Depth
BB	Biomass Burning
BC	Black Carbon
BrC	Brown Carbon
BHI	Beam Horizontal Irradiance
CAMS	Copernicus Atmosphere Monitoring Service
CAPs	Cold Air Pools
CMF	Cloud Modification Factor
c-Si	Crystalline Silicon
DNI	Direct Normal Irradiance
DT	Digital Twin
GHI	Global Horizontal Irradiance
KDE	Kernel Density Estimation
kWp	Kilowatt-peak
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
PBL	Planetary Boundary Layer
PM10	Particulate Matter (diameter > 10 micrometers)
PM2.5	Particulate Matter (diameter < 2.5 micrometers)
POA	Plane of Array
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RECs	Renewable Energy Communities
RMSE	Root Mean Square Error
RTM	Radiative Transfer Model
SSA	Single Scattering Albedo
SVF	Sky-View Factor
UTC	Coordinated Universal Time
WHO	World Health Organization

Appendix A. Dust Events

This appendix provides supplementary empirical data about the impact of severe Saharan dust intrusions on PV performance. Figure A1 summarizes the percentage of daily energy loss across five major dust events in 2024, correlated directly with the peak Dust Aerosol Optical Depth (AOD) of each event. Figures A2 and A3 present a detailed time-series of key parameters for the prolonged April 2024 dust episode at both the ground-based (Koutselio) and rooftop (Mpafra) sites. These plots demonstrate the direct sequence of events as AOD crosses the extreme threshold (>0.5), severe scattering heavily attenuates the direct beam irradiance, which consequently drives to a severe reduction in actual PV power generation against the established clear-sky empirical baselines.

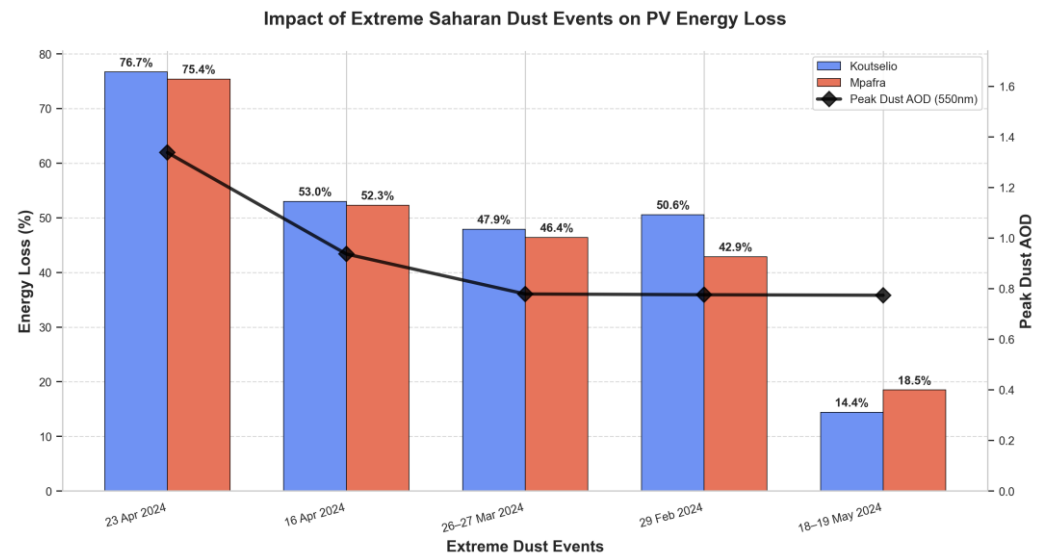


Figure A1. Comparative analysis of daily PV energy loss (%) at the Koutselio (blue) and Mpafra (red) installations during five extreme Saharan dust events. The solid black line corresponds to the Dust AOD (550 nm) peak recorded for each event.

It should be noted that the temporal evolution of Dust AOD appears nearly identical in Figures A2 and A3 because both PV sites are geographically close and thus, fall within the same coarse spatial grid (~80 km) of the CAMS regional product. The negligible variations observed between the two AOD curves arise solely from spatial interpolation, as the exact coordinates of each site receive slightly different weighting from the four corner nodes of the grid cell. Consequently, the BHI curves, which were directly derived from the GHI and DNI simulated via the libRadtran radiative transfer model, are also highly similar, as they are driven by this shared regional AOD input and the nearly identical solar geometries of the closely situated plants. Despite this shared atmospheric forcing and the nearly equal installed capacity (~100 kWp) of the two installations, the magnitude of the actual PV power output differs significantly. This discrepancy is primarily driven by the differing module efficiencies (24% for Koutselio vs. 18% for Mpafra) and their distinct installation geometries (ground-based at a 33° tilt vs. rooftop at a 15° tilt), which dictate the final energy conversion capabilities under the same atmospheric attenuation.

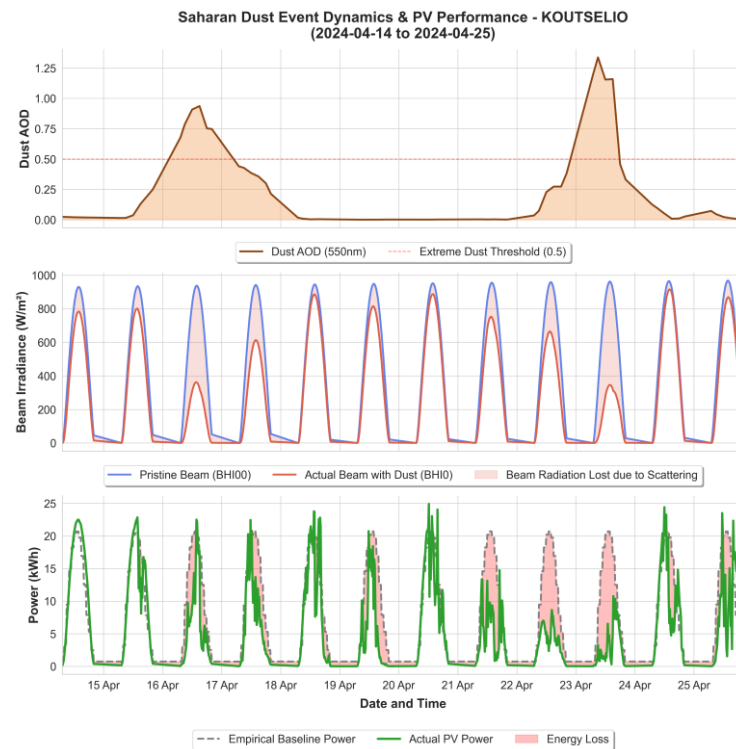


Figure A2. Temporal dynamics of the April 14–25, 2024 Saharan dust intrusion and its direct impact on the Koutselio PV plant. The panels sequentially display: (**top**) the progression of Dust AOD (550 nm) exceeding the extreme threshold of 0.5; (**middle**) the severe attenuation of direct-beam irradiance (BHI) due to optical attenuation (indicated by the red shaded area); and (**bottom**) the resulting severe deficit in empirical PV power generation compared to the clean-day baseline (red shaded area).

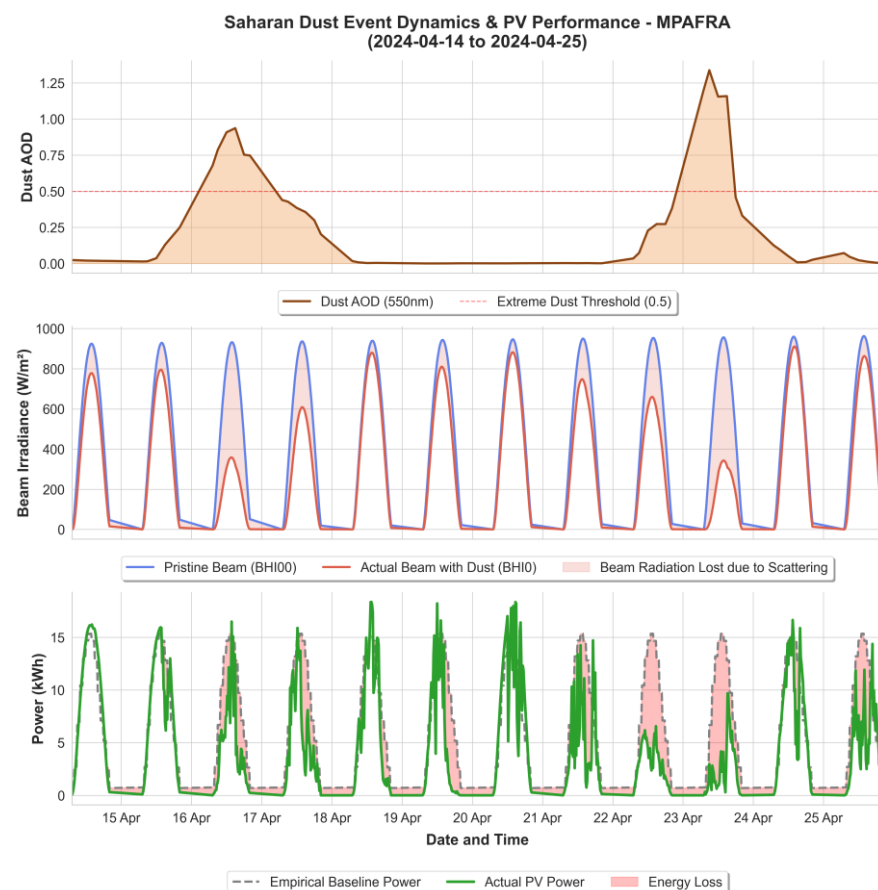


Figure A3. Temporal dynamics of the April 14–25, 2024 Saharan dust intrusion and its direct impact on the Mpafra rooftop PV plant. Similar to the ground-based site, the panels sequentially display: **(top)** the progression of Dust AOD (550 nm); **(middle)** the heavy attenuation of direct-beam irradiance (BHI) due to optical attenuation (indicated by the red shaded area); and **(bottom)** the resulting power generation deficit against the empirical baseline.

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