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FORECASTING PV OUTPUT DURING AEOLIAN DUST EVENTS: A CASE STUDY IN THE EAST MEDITERRANEAN

Summary

As photovoltaic (PV) systems expand, especially in isolated grids like islands, their performance is increasingly affected by aeolian dust events that reduce solar irradiance and soil panels, leading to unpredictable power losses. This variability raises operational and financial risks, requiring advanced forecasting tools. To address this, a new forecasting system is being developed using high-resolution atmospheric modelling (WRF-Chem) and solar radiation data from Copernicus Atmosphere Monitoring Service (CAMS), combined with real-world data from over 500 PV systems over the island of Cyprus. The model aims to predict dust-related energy losses, optimise cleaning schedules, and support decision-making, with potential applications across the Eastern Mediterranean and Middle East dust-prone regions.

Keywords: Solar PV, Aeolian Dust, WRF-Chem, CAMS

1. Introduction

The integration of photovoltaic (PV) systems into national electricity portfolios is rapidly advancing, driven by climate and energy policies promoting renewable energy sources. In small, isolated grids such as the island of Cyprus, where PV capacity is expected to exceed 1 GW by 2027, the variability of solar power presents a significant challenge for system operators. These challenges are amplified in regions affected by frequent atmospheric dust events, which reduce solar irradiance and accumulate on panels, leading to substantial and often unpredictable reductions in power output. Aeolian dust presents a dual challenge, it both attenuates incoming solar radiation and reduces PV panel efficiency through soiling. In addition to reducing radiation, dust deposition causes soiling, which further lowers power output. Mitigating these effects, whether from dry or wet deposition, requires labour-intensive cleaning processes, significantly raising maintenance costs. Accurate forecasting of dust deposition allows for the optimisation of cleaning schedules, reducing operational costs and improving system efficiency.

Variable energy sources are inherently risky due to the uncertain cashflow profiles resulting from variable output and weather-dependent demand. This financial risk drives up capital costs and exacerbates uncertainty, leading to slower market uptake and often requiring fiscal support mechanisms. Isolated dust events, such as 3-day storms, have been shown to cause economic losses for solar PV systems (Monteiro, 2022). Some studies indicate that the presence of mineral dust can reduce output by up to 80%, while long-term increases in dust episodes, driven by climate change, can lead to efficiency losses as high as 12.7% (Hachicha, 2019). Current solar forecasting approaches typically focus on cloud dynamics and irradiance patterns, without accounting for airborne dust impacts. While the dual threat of aeolian dust is recognised, few forecasting models integrate real-time dust dynamics to predict its effects on solar energy production. This is particularly critical in regions like Cyprus, where limited grid flexibility, high curtailment rates, and the absence of large-scale energy storage heighten the need for advanced forecasting tools that incorporate such disruptions. Even modest improvements in forecasting can lead to substantial operational and economic gains for small island systems.

2. Methodolgy

To address this gap, we are developing a comprehensive forecasting system that combines high-resolution atmospheric modelling with real-world solar data from over 500 PV systems across Cyprus. Using solar radiation data from the Copernicus Atmosphere Monitoring Service (CAMS), alongside the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem), we simulate regional dust transport and radiative feedbacks using the configuration outline in Table 1. CAMS provides satellite-derived estimates of surface solar irradiance, including Direct Normal Irradiance (DNI), on a 0.2° grid, offering a consistent and up-to-date dataset for evaluating atmospheric conditions. By analysing DNI values together with PV production records, we detect performance reductions during dust-affected periods. Our methodology estimates panel soiling rates and correlates dust load data with PV energy output through statistical and machine learning techniques, while accounting for the time-lagged effects of dust deposition.

Tab. 1: WRF-Chem model configuration options used in the simulations.

Process	Option	Reference
Microphysics	Morrison two-moment scheme	Morrison et al. (2005)
Land surface	NOAH Land Surface Model	Chen and Dudhia (2001)
Boundary layer	Yonesi University (YSU) planetary boundary layer	Hong et al. (2006)
Cumulus	Grell 3D Ensemble Scheme	Grell and Dévényi (2002)
Surface layer	MM5 Similarity Surface Layer Scheme	Zhang and Anthes (1982)
Radiation	Rapid Radiative Transfer Model (RRTMG)	Iacono et al. (2008)
Gas-phase chemistry	Regional Atmospheric Chemistry Mechanism (RACM)	Stockwell et al. (1997)
Aerosols	Model Aerosol Dynamics Model for Europe (MADE)	Ackerman et al. (1998)
	Secondary Organic Aerosol Model (SORGAM)	Schell et al. (2001)

3. Results

Establishing a robust correlation between observed dust concentrations, dust optical depth and PV output, enables the development of a forecasting framework to predict energy losses and estimate uncertainty bounds for operational planning. As shown in Figure 1, elevated coarse particulate matter (PM_{10}) concentrations during an aeolian dust event correspond with a notable reduction in solar DNI. We assess the model's applicability in the Eastern Mediterranean and Middle East, where similar limitations in forecasting capacity and grid flexibility exist. WRF-CHEM model outputs (extinction coefficient, optical depth and concentrations) are qualitatively and quantitatively evaluated against in situ and remote sensing observations. Total column and vertically resolved aerosol optical properties are acquired by ground-based AERONET sun photometers, while near-surface concentrations are validated against the European Monitoring and Evaluation Programme (EMEP). Satellite-derived vertical dust and columnar aerosol optical properties are compared with LIVAS (LIdar climatology of Vertical Aerosol Structure) and MIDAS (ModIs Dust AeroSol). We also find that in cases of high aerosol loadings, the model predictive skill is improved when WRF-Chem simulations are initialised with the meteorological fields of Aeolus wind profiles assimilated by the IFS. The improvement varies in space and time, with the most significant impact observed during the autumn months in the study region.

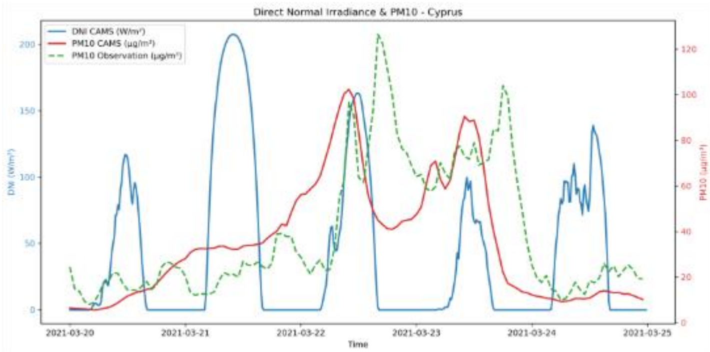

Figure 1: DNI and PM10 Concentrations in Cyprus (20–25 March 2021). Time series of CAMS modelled Direct Normal Irradiance (DNI, blue line, left y-axis) and PM10 concentrations from CAMS (red line) and observations from the Department of Labour, Cyprus (green dashed line; right y-axis). Elevated PM10 levels between 22–24 March coincide with significant reductions in DNI, highlighting the impact of particulate matter on solar irradiance.

4. Conclusion

The proposed forecasting tool is expected to support grid operators and PV asset managers by providing near-real-time predictions of dust-related output reductions and by suggesting optimal cleaning or curtailment strategies. In the long term, this system could improve the net present value of PV investments by reducing performance uncertainty and operational costs. As electricity systems evolve towards decentralised and renewables-based structures, forecasting tools that account for dust impacts will become essential, not only in Cyprus, but across the broader Mediterranean and other arid and semi-arid regions globally.

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6. References

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