

Virtual Mobility (VM) Grant Report

Title: Quantifying Dust Radiative Effects on Solar Radiation and Photovoltaic Output over the Mediterranean Basin using AERONET Observations and Radiative Transfer Simulations

VM Beneficiary: Georgia Charalampous

Host Institution / Expert: Dr. Ilias Fountoulakis

COST Action: CA21119

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1. Introduction

The Mediterranean Basin is frequently affected by mineral dust intrusions from North Africa and the Middle East, which significantly alter the atmospheric radiative balance and impact solar energy production. Given the region's rapid expansion of photovoltaic (PV) installations, quantifying the direct radiative effects (DRE) of dust and their consequences on PV performance is of high scientific and societal relevance.

This VM builds upon work initiated during the Berlin Harmonia School, where preliminary event-based analyses were conducted. The aim of the present VM was to extend that work with radiative transfer (RT) simulations and PV yield modeling, evaluating both event-specific impacts and sensitivity to aerosol optical properties.

2. Aims and Objectives

The main objectives of this VM were to:

- Quantify the DRE of dust on surface shortwave radiation during representative dust events in the broader Mediterranean Basin for the period 2021–2022.
- Assess the reduction in PV electricity production using the GSEE model.
- Perform sensitivity experiments to investigate the effect of Single Scattering Albedo (SSA), Asymmetry Parameter (ASY), Angstrom Exponent (AE), Aerosol Optical Depth (AOD), and Solar Zenith Angle (SZA) in solar radiation and, in turn, solar energy.
- Provide input for improving dust representation in solar energy forecasting and WG3 deliverables.

3. Methodology

- Observations: AERONET Level 1.5 Version 3.0 (Giles et al., 2019) retrievals of AOD, SSA, AE, and ASY for stations across the Mediterranean and Middle East. The aforementioned parameters were derived for two spectral areas, one in the ultraviolet spectral region (UV) and one in the visible (VIS) (Table 2).
- Event Selection: Four major dust outbreaks:

Table [1] : The representative dust events and the respective stations that were used to investigate the dust radiative effects and the effect in solar energy production.

18 – 29 March 2021	17 – 28 June 2021	10 – 21 November 2021	21 April – 1 May 2022
Antikythera	Antikythera	Sede Boker	Lampedusa
Cairo	Athens	Weizmann Institute	Mallorca
Finokalia	Ben Salem	Cairo	Rome
Nicosia	Rome	Agia Marina Xyliatou	Valladolid
Sede Boker	Magurele-Inoe	IMS-METU-ERDEMLI	Athens
Limassol	Thessaloniki	Finokalia	CUT-TEPAK

- Modeling: Radiative transfer simulations with libRadtran/DISORT model, covering 280–3000 nm, with realistic atmospheric profiles.

Table [2] : Specifications of input atmospheric parameters in RT simulations for realistic conditions, based on the different spectral ranges, ultraviolet (UV) and visible (VIS).

Parameter	Simulated Radiances (280-500 nm)	Simulated Radiances (500-3000 nm)
AOD	440 nm	500 nm
AE	380-500 nm	440 - 675 nm
SSA	440 nm	675 nm
ASY	440 nm	675 nm
CO2	410 ppb	
O3	300 DU	

- Table [3] : Sensitivity Analysis:

Parameter	Range of input parameter	Step
AOD	0-1.6	0.2
AE	0-0.4	0.2
SSA	0.84-0.89	0.03
ASY	0.62-0.82	0.04
SZA	0-75	15 degrees

- PV Modeling: GSEE used to simulate PV output under both baseline and dust-perturbed irradiance. The model includes modules that enable the simulation of a complete PV

system, incorporating parameters such as the install capacity, technology (c-Si, CdTe), tracking (fixed, 1 or 2 axis), tilt angle and orientation. The user provides as input solar radiation data, and optionally, ambient temperature and surface albedo.

4. Results

Calculation of solar radiation and solar energy losses

4.1 Event-Based Analysis

- DNI reductions exceeded 70–90% during peak AOD.
- GHI reductions ranged from 20–40%.
- PV output losses were typically 25–45% on daily scales, occasionally ~60% during the most intense episodes.
- Source-proximal sites (Cairo, Nicosia, Sede Boker) showed the strongest reductions, while western Mediterranean sites (Mallorca, Valladolid) were less affected but still notable.

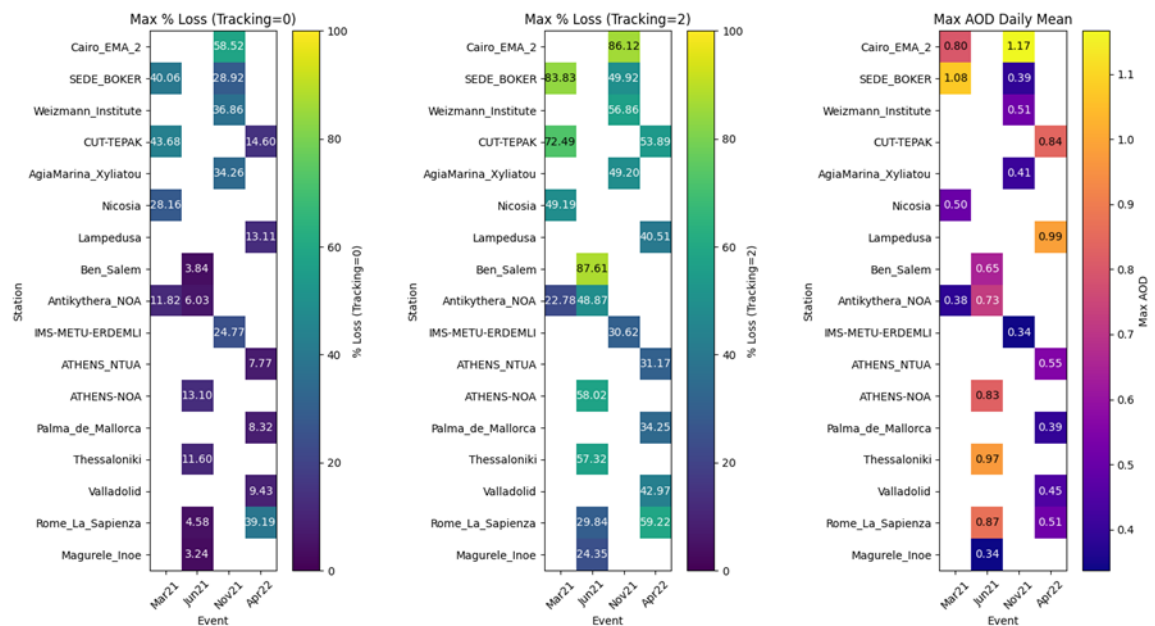


Figure [1]: Comparison of the maximum percentage losses in photovoltaic (PV) energy production during the four major dust events (March 2021, June 2021, November 2021, and April–May 2022) across selected Mediterranean and Middle Eastern AERONET stations. The left and middle panels show maximum energy losses for fixed-tilt (Tracking = 0) and dual-axis tracking systems (Tracking = 2), respectively, while the right panel presents the corresponding maximum daily mean aerosol optical depth (AOD) at 500 nm.

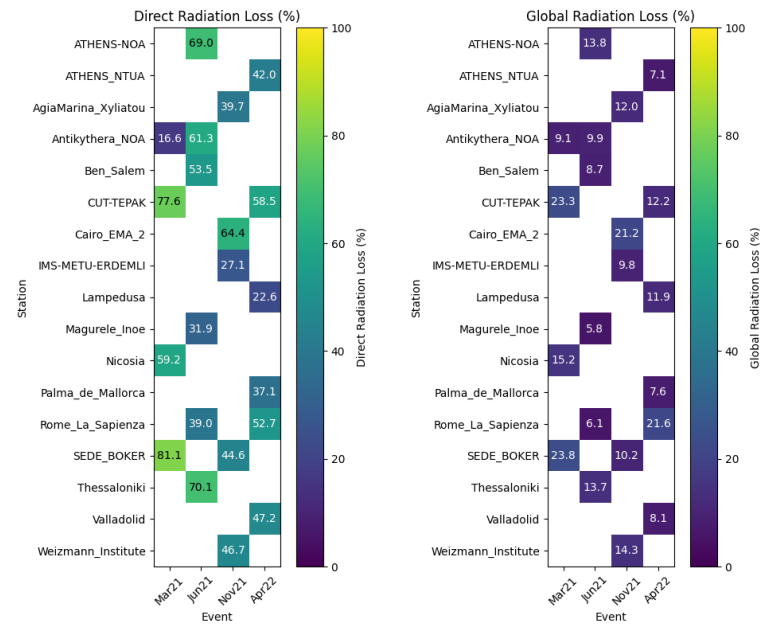


Figure [2]: Percentage losses in Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) during the four dust events across selected AERONET stations.

4.2 Sensitivity to Optical Properties

- Losses increased sharply with SZA and AOD, especially under absorbing dust ($SSA < 0.85$).
- SSA effect: Lower SSA yielded losses up to 80%; nearly scattering dust ($SSA \rightarrow 1.0$) showed $<20\%$ losses under most conditions.
- AE effect: Coarse dust ($AE = 0.0-0.2$) amplified losses relative to finer aerosols.

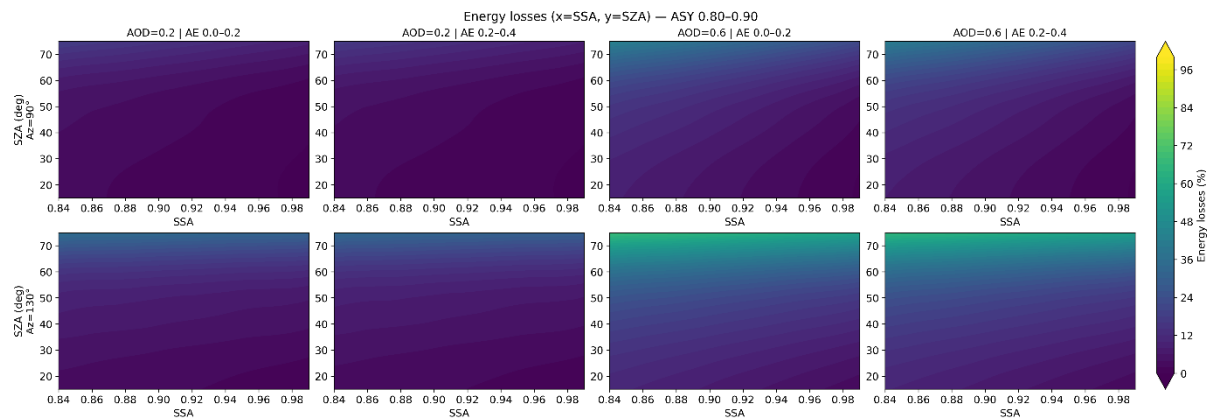


Figure [3]: Sensitivity of solar energy losses (%) to variations in single scattering albedo (SSA) and solar zenith angle (SZA) for different combinations of aerosol optical depth (AOD) and Ångström exponent (AE), assuming an asymmetry parameter (ASY) range of 0.80–0.90 and latitude 35° N.

5. Future Work

- Extend simulations to additional years to better quantify interannual variability.
- Integrate findings into METAL-WRF regional model runs for comparison with libRadtran.
- Link PV yield losses to economic and grid-integration impacts for renewable energy planning.
- Contribute to WG3 deliverables on dust–solar energy interactions and forecasting improvements.

6. Link to COST Action Objectives

This VM directly supports the COST Action goals of:

- Advancing understanding of aerosol radiative effects in the Mediterranean.
- Providing tools for improved solar resource forecasting, critical for renewable energy integration.
- Strengthening collaboration across observational and modeling communities established during the Berlin Harmonia School.

7. Conclusions

The VM demonstrated that dust storms represent a major challenge for solar energy production in the Mediterranean Basin, causing daily PV yield losses up to 60% and cumulative event-scale losses of 10–20%. Sensitivity experiments confirmed that these impacts are governed not only by AOD but also by SSA, AE, ASY, and solar geometry. These results underline the need to integrate dust optical properties into operational forecasting tools to ensure reliable solar energy integration in dust-prone regions.

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