Reply to Reviewer#1

Citation: https://doi.org/10.5194/egusphere-2026-2775-RC1

- **Major comments**

- ***#1:*** *Please include a clear definition of the reported losses, preferably including the corresponding equation. The reference used to compute the percentage losses should be explicitly stated. Some related definitions appear later in the manuscript (line 375), but this concept should be introduced earlier and described in greater detail.*

Answer: The corresponding equation regarding the reported losses was included in section 3.1 – Results and discussion and linked to the figures including the respective results, as follows:

Lines 388-392:

"The resulting irradiance and PV energy losses are expressed relative to aerosol-free atmospheric conditions. More specifically, the afore-mentioned losses were calculated based on the following formula:

$$\text{Losses } (\%) = \frac{(\mathrm{R_{clear-sky}} - \mathrm{R_{all-sky}})}{\mathrm{R_{all-sky}}} * 100 \quad (3)$$

Where R denotes the respective parameter in each case; DNI and GHI for radiation losses (presented in Fig.3) and solar energy for PV losses (presented in Fig. 4)"

- ***#2:*** *A map showing the geographical distribution of the considered sites would help the reader better understand the study area and the analysis presented in Section 2.*

Answer: A map presenting the stations in which this study was based was included along with the following description in Section 2.3.

Lines 184-189:

"The selected stations under study are shown in Fig. 1 (also see Fig.1 in Papetta et al., 2026 for the different cases in detail)."

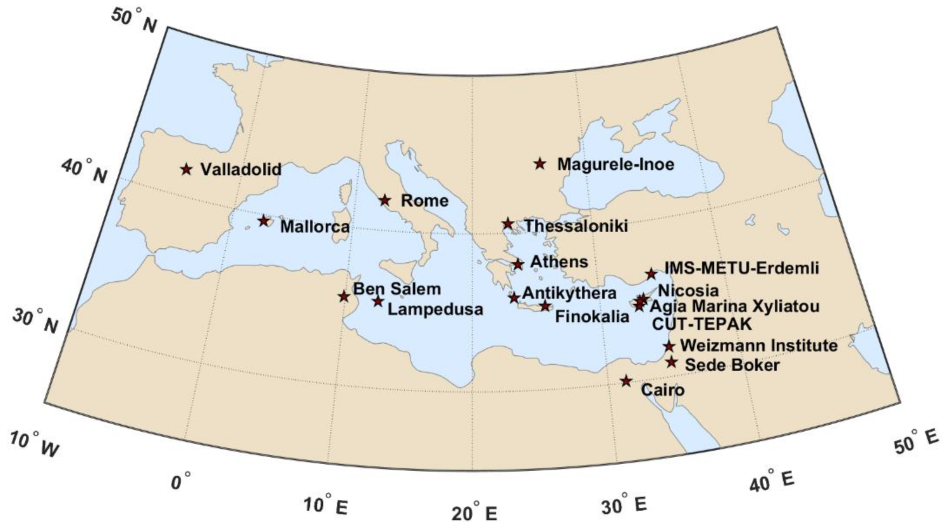

Figure 1: Spatial distribution of all AERONET stations across the Mediterranean Basin used in this study during the different dust events."

- ***#3:*** *Methodology: a description of the broadband radiation measurements is missing. Please provide information on the measurement sites, instruments/sensors, measured variables, quality-control procedures, and any other relevant details.*

Answer: A sub-section was added in Section 2, "2.2 Solar radiation measurements" including a description of the broadband radiation measurements as follows:

Lines 163-170:

"2.2 Solar radiation measurements

Broadband solar radiation measurements from ground-based pyranometers were also used in the frame of this study, providing timeseries of global (GHI) and diffuse (DHI) surface solar irradiance. More precisely, the afore-mentioned observations were used to identify the cloudy and clear-sky conditions (for SZA<80º, GHI-DHI<120 W/m^2 denoted the presence of clouds) during two selected events for two different stations, Lampedusa and Agia Marina Xyliatou. In addition, they were used to directly validate the model-derived radiation parameters, GHI and DHI, as well as to calculate the produced PV energy. The specific sensors provide high-quality measurements, with uncertainties not exceeding 2% for hourly totals and 1% for daily totals over the wavelength range 280-2800 nm at a 1-minute temporal resolution."

- ***#4:*** *How is GTI obtained from SSR? Please clarify the procedure used for this conversion, as this step can introduce significant uncertainties. If this calculation is performed internally within GSEE, please state so and briefly describe the methodology in Section 2.*

Answer:

GSEE requires the GHI as input, and optionally the diffuse fraction (DHI) to calculate $k_d = \frac{DHI}{GHI}$. If DHI is not available, the GSEE includes an implementation of the BRL diffuse fraction model. Next, GSEE internally calculates the plane-of-array irradiance, by applying trigonometric calculations, which also account for the surface albedo and the ground-reflected component of irradiance. While under moderate aerosol conditions the parameterization of the diffuse component is quite accurate, under high dust loads, BRL underestimates DHI. Under very high dust loads (~ 1), the underestimation of the diffuse SSR fraction can result in errors in the simulated energy production of the order of 2% and 5% for fixed and solar-tracking panes respectively (Papadimitriou et al., 2026).

A respective description has been added to the manuscript as follows (lines: 294-305):

"Transposition to the PV plane is done considering the GSEE default optimal tilt angle model (http://www.solarpaneltilt.com/#fixed) and the BRL output (direct and diffuse components calculated considering solar angles), internally by GSEE. GSEE requires the GHI as input, and optionally DHI to calculate the diffuse fraction (k_d):

$$k_d = \frac{DHI}{GHI} \quad \text{(Equation 2)}$$

If DHI is not available, the GSEE includes an implementation of the BRL diffuse fraction model. As a next step, GSEE internally calculates the plane-of-array irradiance, by applying trigonometric calculations, which also account for the surface albedo and the ground-reflected component of irradiance. While under moderate aerosol conditions the parameterization of the diffuse component is quite accurate, under high dust loads, BRL underestimates DHI. Under very high dust loads (~ 1), the underestimation of the diffuse SSR fraction can result in errors in the simulated energy production of the order of 2% and 5% for fixed and solar-tracking panes respectively (Papadimitriou et al., 2026). More uncertainties are introduced due to uncertainties in the GSEE input parameters (SSR, surface albedo, temperature), as well as on uncertainties in the parameterization of losses on the panels and the inverter system, and uncertainties related to dust deposition on the panels."

- ***#5:** The description of the GSEE implementation is not sufficiently detailed. Please specify explicitly which irradiance components (GHI, DHI, DNI and/or plane-of-array irradiance) were provided as inputs to GSEE for each simulation setup (measurements, libRadtran and METAL-WRF) and clarify whether the transposition to the PV plane was performed internally by GSEE. Also include some details in the PV generation model.*

Answer:

GSEE is a widely used open-access model designed for rapid calculations of PV energy production. It considers the position of the sun, as well as the panel's tilt angle and orientation. Transposition to the PV plane is done considering the GSEE default optimal tilt angle model (http://www.solarpaneltilt.com/#fixed) and the BRL output (direct and diffuse components calculated considering solar angles), internally by GSEE.

To clarify the model implementation, we have expanded the description in Section 2.7 together with the additions made to address the previous comment. We now explicitly state that GHI is used as the primary input to GSEE, while DHI can optionally be provided. The irradiance components used for each simulation setup (measurements, libRadtran, and METAL-WRF) are also explicitly specified in the corresponding sections of the manuscript and are also indicated in the relevant figures (e.g., Fig. 14).

- ***#6:*** *Figure 4: please clarify what is meant by "solar energy loss". Does it refer to tilted irradiance, PV energy production, or another quantity? Also indicate the reference used for the normalization and percentage calculations.*

Answer:

Solar energy loss refers to the decrease in PV energy production. Calculations have been performed with respect to the PV output under aerosol-free skies, with all other conditions kept the same.

A clarification was added in lines 407-408 as follows:

"Solar energy losses refer to the decrease in PV energy production. The percentage losses have been calculated relative to the PV output under aerosol-free skies (Eq.3), with all other conditions kept identical."

In addition, the term "PV" was added before "solar energy" in Fig. 5 (previously Fig.4) caption, to clearly indicate that the figure presents PV energy losses.

- ***#7:*** *Please include the optimum fixed tilt angle used at each site.*

Answer:

The tilt angles have been calculated using the default GSEE function. The equation used for the calculations was included in the manuscript, as follows (lines: 288-293):

"For fixed panels, the tilt angles were calculated using the default, built-in latitude linear function included in the GSEE model, considering also a south orientation of the PV panels.

More precisely, the optimum tilt angles (OTAs) of the fixed-tilt systems were calculated using the following function (for latitudes > 25° and latitudes < 50°):

$$OTA = (Lat. * 0.76) + 3.1)\ (1)”$$

Additionally, a table where all the stations, their coordinates and the respective angles are listed in detail, was included in the supplement (S1).

- ***#8:** Please provide more details on the clear-sky selection procedure.*

Answer: An additional comment was included in Sect. 2.2 where the ground-based solar radiation measurements are described, and in Sect. 3.3 to define the clear-sky selection procedure.

Lines 502-503:

“More precisely, days were identified as clear-sky when GHI and DHI components exceeded 120 W/m^2 for SZAs <80º and exhibited a smooth diurnal curve with no rapid fluctuations.”

➢ **Minor comments:**

- ***#1:** L35 - Please clarify that the sensitivity analysis is performed under clear skies conditions*

Answer: A clarification was added in the following sentence between lines 34-37: “The results ... under clear-sky conditions... between 5% and 25%.”

- ***#2:** Fig.1. the figure is difficult to interpret. Is the color coding important for the analysis? If so, please clarify its meaning and improve readability.*

Answer: The colors in Fig.2 correspond to the different combinations of inputs and outputs regarding the Radiative Transfer simulations. We understand it might cause some confusion and, therefore, we added the following description in Sect. 2.4, right before the figure.

Lines 235-242:

“On the left side, the inputs representing the realistic atmospheric conditions (AOD, AE, SSA, ASY and PW) are listed for the two spectral regions as described in (a), allowing the RT simulations to account for the spectral dependence of aerosol radiative effects. On the right side, the parameters (AOD, AE, SSA, ASY, and SZA) used in the frame of a sensitivity analysis described in (b) are presented. A more detailed description of the sensitivity analysis is provided in Section 2.6. Finally, the dark and light grey colours indicate the different wavelength ranges of the RT model inputs that were used to calculate the corresponding GHI and DNI, whose integration over the respective spectral intervals yielded the total broadband BOA irradiances. The sensitivity analysis (shown in dark blue) was performed over the full 280-3000 nm wavelength range."

- ***#3:*** *There is a mismatch between figure numbering and the figure references in the text. (e.g. Figures 5, 6 and 7). Please check figure numbering throughout the manuscript. Also, use a consistent format when referring to figures. For example Fig. X.*

Answer: The numbering and format of the figure references has been revised to ensure consistent use of "Fig. X" format throughout the manuscript.

- ***#4:*** *Sec 3.3 Please refer to figures in order of appearance. For example, Fig. 11 appears referenced before Fig. 9.*

Answer: The reference to (previously) Fig. 11 was removed from the beginning of the Section, and introduced later, right before the respective figure.

- ***#5:*** *L260: fixed tilt: which angle?*

Answer: This comment was addressed in our response to Major comment #7; The fixed tilt angle refers to the optimum fixed-tilt angle used for each PV system, which was calculated using the default GSEE function for the applicable latitude range.

- ***#6:*** *Fig. 9 and Fig. 11: please indicate which days are considered clear-sky cases.*

Answer: The specific clear-sky days were mentioned in the manuscript (lines: 502-504) but, to avoid confusion, they were also specified in the respective figure's caption as follows:

Caption of Fig. 10 (previously Fig. 9):

"...In the case of AMX, during days 2, 3, 5 and 7 clear-sky conditions dominated, while in the case of Lampedusa, days 1, 6, 7, 8 and 9 indicated cloudy conditions."

In Fig. 12 (previously Fig.11), where the comparison between model and measurements are presented, the cloudy sky days were removed completely to avoid confusion.

- ***#7:*** *In the sensitivity analysis, please specify the wavelength associated with the reported AOD values.*

Answer: The wavelength associated with the reported aerosol properties values was included in Sect. 2.6, lines 272-274 as follows:

"... (AOD at 500 nm, AE for 440-670 nm, SSA at 675 nm, ASY at 675 nm, and SZA)..."

And also denoted in Table 2, as follows:

Parameter	Range	Step
AOD_{500}	0-1.6	0.1
$AE_{440-670}$	0-0.4	0.2
SSA_{675}	0.84-0.99	0.03
ASY_{675}	0.62-0.82	0.04
SZA	0-75°	15°

- ***#8:*** *Fig. 11 and Fig. 1comparing outputs from a clear sky radiative transfer model (libRadtran in this case) with measurements affected by cloudiness is difficult to interpret and does not provide a meaningful assessment of model performance.*

Answer: The authors agree, the comparison under cloudy-sky conditions was excluded and the respective figures have been replaced. The updated figures 12 and 14 (previously 11 and 13, respectively) are the following, where the results presented correspond to comparisons only during clear-sky days:

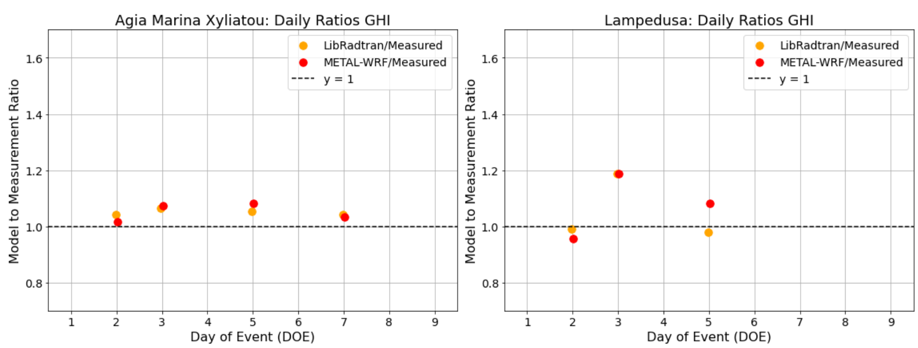

Figure 12: Ratios of GHI from libRadtran (orange) and METAL-WRF (red) to measured GHI at Agia Marina Xyliatou (left) and Lampedusa (right) for clear-sky days.

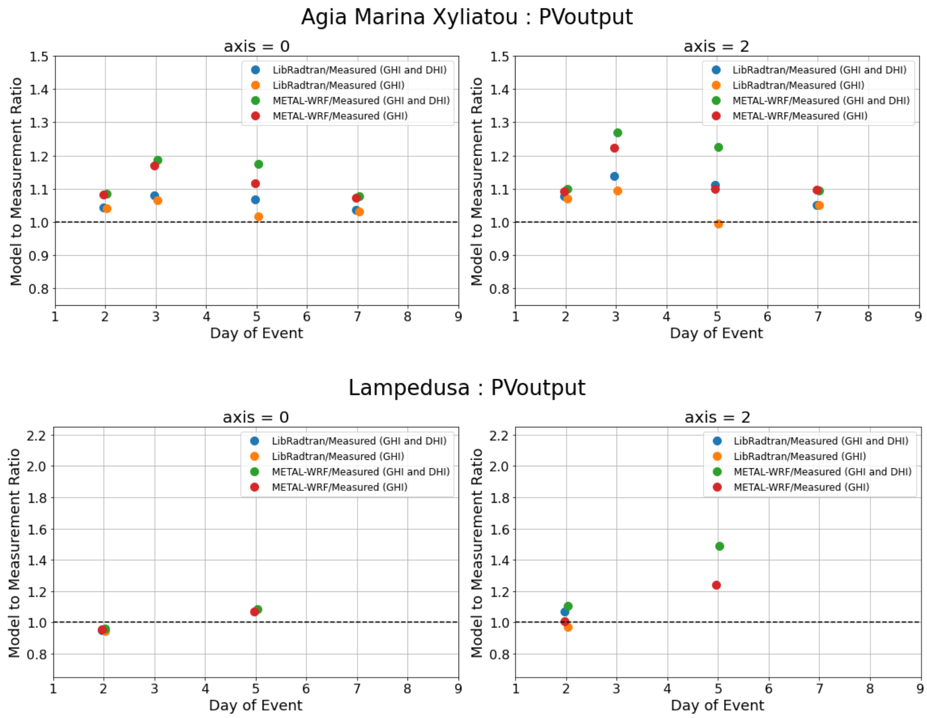

Figure 1: Ratios between PV_{lbr} and PV_{wrf} for Agia Marina Xyliatou (upper panels) and Lampedusa (lower panels), for clear-sky days and for two panel setups: optimally inclined PVs (left panels), and 2-dimensional solar tracking PVs (right panels).

- ***#9:*** *conclusions: consider removing "Under cloudy conditions, the comparisons lead to greater differences and an overall overestimation in the case of libRadtran", as this result is expected when comparing clear-sky simulations with cloudy-sky observations.*

Answer: The authors agree, the sentence was removed from the conclusions.

- **Suggestions:**

- ***#1:*** *Consider including a glossary of the main acronyms and variables used throughout the manuscript.*

Answer: We thank the reviewer for the suggestion. A table with abbreviations was included at the end of the manuscript.

- ***#2:*** *L120: is there any estimate of the annual energy losses associated with dust events over the study region? Although outside the main scope of this work, such information could help place the reported event-scale impacts into a broader context.*

Answer: A reference to another study by Verga et al. (2026) was already included in the introduction of the manuscript, which discusses the annual energy losses associated with dust events over the study region. To improve clarity, we have slightly rephrased the relevant sentence (Lines 121-122):

“In a more recent study, Varga et al. (2026) showed that Saharan dust events reduce PV output across the Mediterranean countries by an average of 25–40% on an annual basis, with losses exceeding 50% during extreme events.”

- ***#3:*** *Since completely clear days are relatively scarce, the authors could consider using clear-sky periods selected from different days (even when a full day is not entirely cloudless) through the application of a clear-sky detection algorithm. This could potentially increase the amount of data available for the final analysis*.

Answer: In Figure 13 our intention is to quantify differences in the simulated daily integrals of the PV output when simulations are based on METAL-WRF or libRadtran instead of measurements. Giving a more analytical graph with individual measurements is out of the scope of this figure. Thus, we decided to keep daily integrals for cloudless days.

Reply to Reviewer#2

Citation: https://doi.org/10.5194/egusphere-2026-2775-RC2

- **Main comments**

- ***#1:*** *The analysis is based on four different dust events. However, using only the station names listed in Table 1 makes it difficult for readers to understand the spatial extent and characteristics of these events. It is recommended to provide additional information describing their spatial distribution and intensity. Furthermore, as the manuscript indicates that solar energy production is strongly influenced by dust aerosol optical depth, it would be helpful to include a brief description of the intensity of each dust event.*

Answer: Some additional information regarding the dust events' spatial distribution and intensity was included in the manuscript in Sect. 2.3, as follows (lines 195-199):

"The four selected dust events covered a wide range of transport regimes and intensities, from a widespread Saharan outbreak with maximum observed daily average AOD reaching 1.08 (Event A), to an efficient mid-tropospheric long-range transport event (Event B), with the maximum daily average AOD reaching 0.97, a spatially confined Middle Eastern outbreak (Event C) with a maximum AOD of 1.17 and a complex multi-source, basin-wide event with moderate dust loading, with daily average AOD not exceeding 1, affecting big part of the Mediterranean (Event D)."

- ***#2:*** *The introduction section lacks a clear and coherent logical structure. For example, after the discussion of atmospheric aerosols, with dust particles as the main focus (lines 57-60), the authors return to a general discussion of aerosols' direct and indirect radiative effects (lines 60-61).*

Answer: The introduction has been updated based on the reviewer's comment.

- ***#3:*** *The authors estimate PV output using ground-based measurements and METAL-WRF for AMX and Lampedusa. However, given the spatial and temporal variation of dust transport and aerosol properties, it would be helpful to explain whether the conclusions drawn from these two case studies can be generalized to the broader Mediterranean Basin. Furthermore, as these two stations are affected by Saharan and Middle Eastern dust events, respectively, it would be useful to discuss whether dust from these distinct source regions has distinct implications for PV energy production and model performance.*

Answer: Lines 590-595, the following explanation was included:

"The chemical composition and microphysical properties of dust, and consequently its optical properties, strongly depend on its source region. Therefore, dust originating from the same source region is expected to exert a similar influence on surface solar radiation (SSR) and, consequently, on PV power output. In this context, the selected cases can be regarded as representative of dust events affecting the Mediterranean Basin, rather than as isolated case studies. Such events regularly influence multiple regions across the Basin through recurring transport pathways, making them suitable case studies for assessing regional-scale impacts."

- **Minor comments**

- ***#1:*** *Lines 64, 75: Please avoid having two sets of parentheses next to each other.*

Answer: The respective parentheses have been adjusted accordingly:

"(DRE; Li et al., 2004; Biagio et al., 2020)", Line 81 in the updated manuscript.

"…with a range of +0.10 and +0.40 W/m2 (Kok et al., 2023)", Line 72 in the updated manuscript.

- ***#2:*** *Line 158: The reason for using Level 1.5 AERONET data should be provided.*

Answer: The reason for using Level 1.5 AERONET data was provided, as suggested, by the implementation of the following sentence, lines 158-160:

"The selection of L1.5 instead of L2 products was made to increase data availability, acknowledging the slightly larger uncertainties (0.01-0.02) associated with the absence of full calibration, especially at low AOD conditions."

- ***#3:*** *Line 174: Need references for the criteria.*

Answer: A reference was included right after the criteria of the selection, line 174: "(e.g., Basart et al., 2009)".

- ***#4:*** *Line 365: It is not clear how the "global direct radiation losses" are defined.*

Answer: The corresponding equation regarding the reported losses was included in section 3.1 – Results and discussion and linked to the figures including the respective results, as follows:

Lines 388-392:

“The resulting irradiance and PV energy losses are expressed relative to aerosol-free atmospheric conditions. More specifically, the afore-mentioned losses were calculated based on the following formula:

$$\mathrm{Losses}\ (\%) = \frac{(R_{clear-sky} - R_{all-sky})}{R_{all-sky}} * 100 \quad (3)$$

Where R denotes the respective parameter in each case; DNI and GHI for radiation losses (presented in Fig.3) and solar energy for PV losses (presented in Fig. 4)”

- ***#5:*** *Line 434: Why are only two stations used?*

Answer:

The two stations have been selected:

(1) because they provide reliable measurements of the required SSR components - not available to most of the selected sites for the desired dates.

(2) because they were affected by events of different origin (Lampedusa/Saharan dust, AMX/Middle East dust) characterized by different optical properties. Thus, Lampedusa was selected as a representative case study of a strong Saharan dust event, while AMX was selected as a representative case study of a Middle East event.

A clarification was added in Section 3.3. where the two cases are introduced, as follows (lines 490-493):

“We focus on two stations affected by dust events of different origin, Sahara (Lampedusa, during event D) and the Middle East (Agia Marina Xyliatou- AMX, during event C), characterized by different optical properties.”

- ***#6:*** *Line 515: “These days have been excluded.” Please be specific.*

Answer: The days were clarified by rephrasing the sentence to:

“More specifically, days 1 and 3 have been excluded…”, lines 573-574.

- ***#7:*** *Please use either "Figure X" or "Fig. X" consistently throughout the manuscript when referring to figures.*

Answer: The format of the figure references has been revised to ensure consistent use of “Fig. X” format throughout the manuscript.

Please note that references cited herein are given in our original manuscript.