

## **Evaluation of the BRL diffuse fraction model under different aerosol scenarios using ground-based radiometric & actinometric measurements, and RT simulations**

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**Grantee name:** Nikolaos Papadimitriou

### **1. Introduction**

PV power modelling enables expressing solar energy in terms of energy production. Achieving PV power output simulations requires the following steps: (i) decomposing Global Horizontal Irradiance (GHI) into Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI) (ii) calculating the plane-of-array irradiance incident on the surface of PV planes, whether static or mounted on a solar tracking system, and (iii) simulating the PV power production primarily based on the in-plane irradiance (Blanc et al., 2017). The first step can be overpassed if exist concurrent measurements of both the irradiance components. However, limited availability of measurements of solar irradiance components at the same time, coupled with the complexity of their theoretical computation, has driven the development of numerous empirical models for estimating the diffuse fraction (ratio of the diffuse-to-global solar radiation), known as diffuse fraction models.

The diffuse fraction models predominantly rely on the clearness index or cloudiness index (ratio of the global-to-extraterrestrial radiation) as the principal predictor, while in some cases incorporate additional predictors for enhanced prediction (Paulescu & Blaga, 2019). Ridley et al. (2010) developed a multiple-predictor logistic model, known as the Boland-Ridley-Lauret (BRL), which combines simplicity and reliable performance across both the Northern and Southern Hemispheres, proposed as a universal model. However, in solar energy modelling is critical to focus on cloud-free skies, where energy production is maximized. Under such conditions, aerosols become the primary parameter influencing the distribution of solar irradiance among its components. The work of Blaga (2024) highlights the inconsistency of estimates due to the aerosol influence. An extension of the classic BRL model, the BRL-min (Starke et al., 2018), involves an estimate of the clear-sky irradiance as an extra predictor, as an effort to incorporate the influence of atmospheric aerosols. The use of BRL-min requires employment of clear sky model which introduces uncertainties. On the other hand, assuming that theoretical estimations of extraterrestrial radiation combining solar geometry and astronomy are reliable, classic BRL implementation is characterized by simplicity, as the provided input practically solely consist of hourly timeseries of GHI.

The main goals of this study is to evaluate the BRL performance under cloud-free sky conditions from ground-based measurements and Radiative Transfer (RT) simulations, considering various

aerosol conditions. Moreover, to assess the extent to which these uncertainties propagate into the PV power generation using the Global Solar Energy Estimator (GSEE; Pgenninger & Staffel, 2016).

## 2. Data and Methodology

We collected ground-based actinometric and temperature measurements from five stations of the Baseline Surface Radiation Network (BSRN; Driemel et al., 2018), while information for aerosols was retrieved from co-located stations of the Aerosol Robotic Network (AERONET; Holben et al., 1998; Dubovik et al., 2000). The examined sites are depicted in Figure 1, while detailed information about their coordinates and altitude is provided on Table 1.

**Table 1.** Detailed information about the location of the ground-based stations used in this study.

| STATION           | Latitude [° N] | Longitude [° E] | Elevation [m] |
|-------------------|----------------|-----------------|---------------|
| Carpentras (CAR)  | 44.08          | 5.06            | 100           |
| Cener (CNR)       | 42.82          | -1.60           | 471           |
| Izana (IZA)       | 28.31          | -16.50          | 2373          |
| Lindenberg (LIN)  | 52.21          | 14.12           | 125           |
| Tamanrasset (TAM) | 22.79          | 5.53            | 1385          |

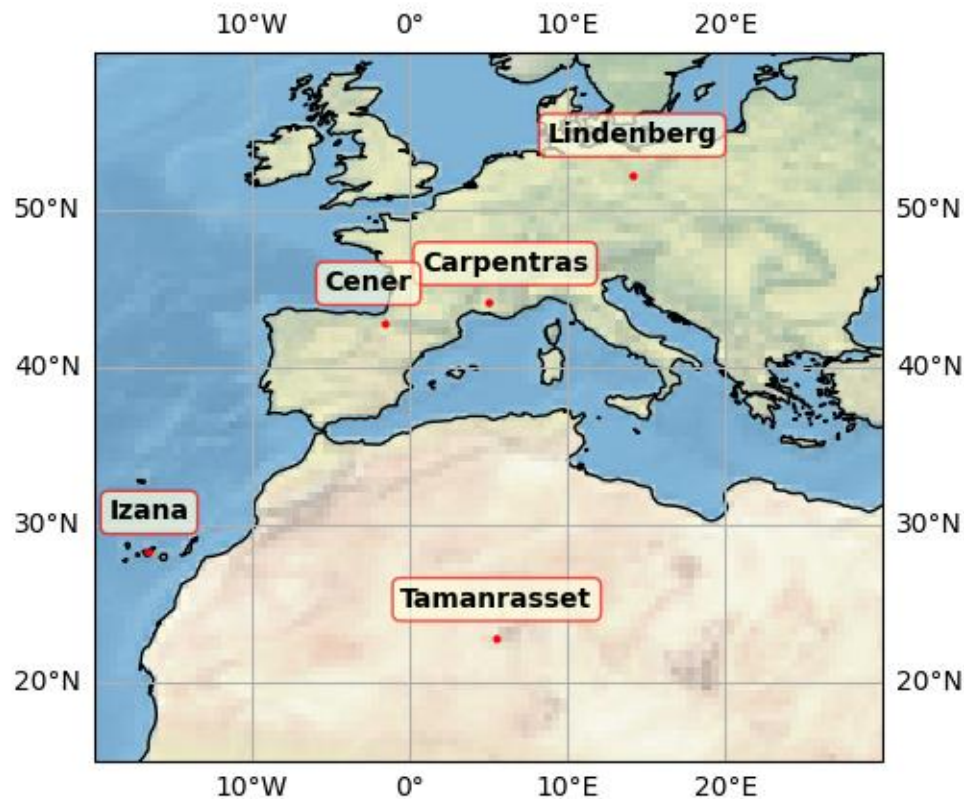


**Figure 1.** Locations of the BSRN and co-located AERONET stations that are used in the current study

The selected sites exhibit a variety of quite different sky conditions. Tamanrasset located in a region which is an important source of Saharan aerosol (Faid et al., 2012) serves as a representative and exceptional case for studying the impact of desert dust aerosol in solar-based power generation. Meanwhile, Izana, located in subtropical North Atlantic, is a high mountain station within the free troposphere, affected by mineral dust when the Sahar Air Layer top exceeds the station height. Due to its high altitude, Izana can be considered as representative of large areas, as it avoids contamination from local or regional sources (Barreto et al. 2022). The Canary Islands, where Izana is located, are influenced by extreme dust events that cause a significant decrease in PV power generation (Canadillas-Ramallo et al., 2021). In South Europe, where Carpentras and Cener are located, the sites are also affected by the transport of Saharan dust across the Mediterranean, so the aerosol types exhibit a mixture as a result of simultaneous local pollution and low concentration of mineral dust (Logothetis et al., 2020). Figure 2, provides a brief summary of the prevailing aerosol conditions among the examined sites.

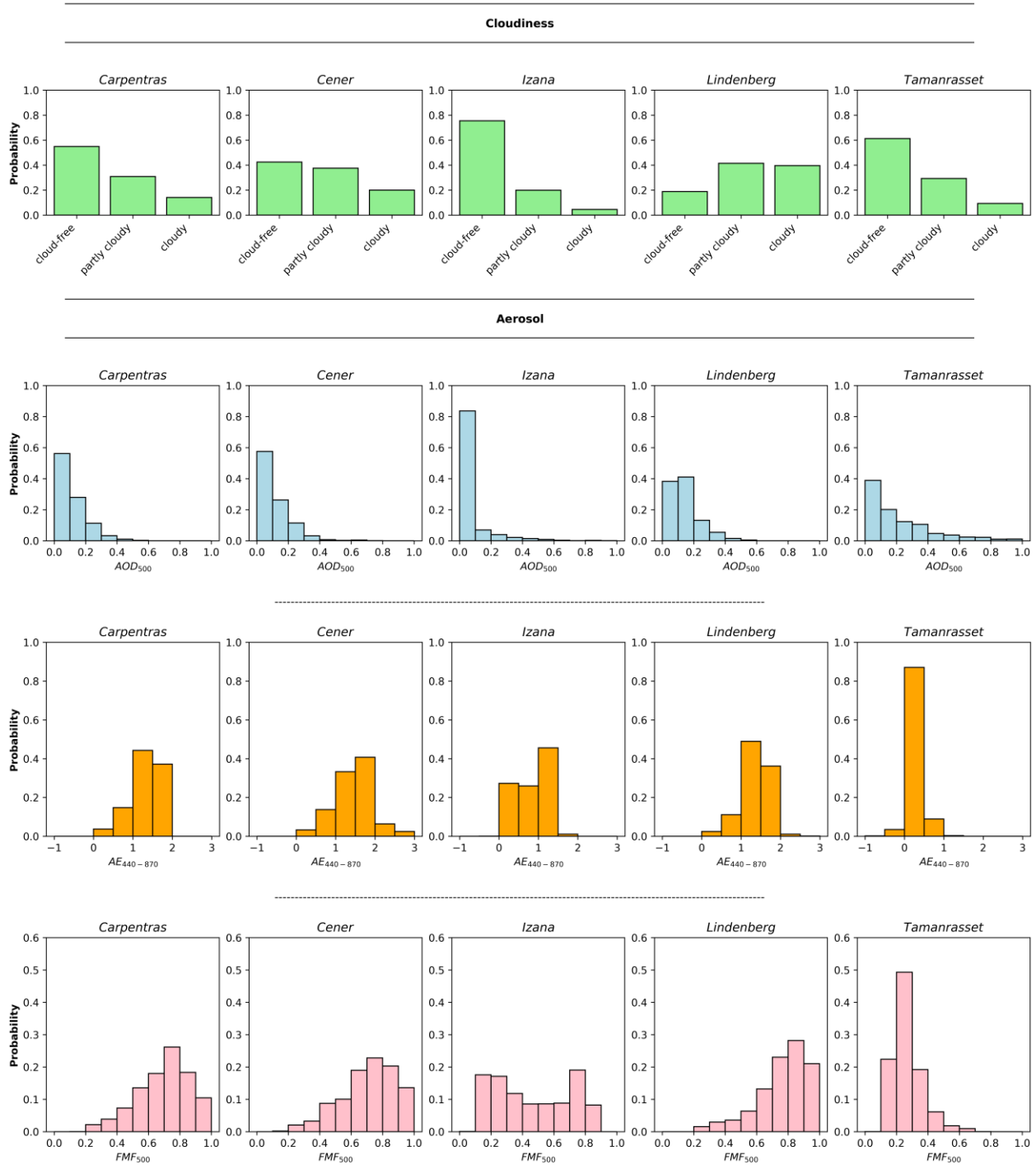


**Figure 2.** Overview of the prevailing sky conditions derived using BSRN and AERONET data

We deployed the Global Solar Energy Estimator (GSEE; Pfenninger & Staffell, 2016) to perform solar energy production simulations with the ground-based radiation data. GSEE includes an implementation of the BRL diffuse fraction model (Ridley et al., 2010; Lauret et al., 2013). We supplied the BRL model with time-series of Global Horizontal Irradiance (GHI) divided with the top-

of-the-atmosphere (TOA) irradiance. We compared the estimated diffuse fraction with the actual derived by dividing Diffuse Horizontal Irradiance (DH) with GHI. To evaluate the model performance under different conditions, first, we distinguished the cloud-free conditions, by utilizing measurements of Direct Normal Irradiance (DNI), relying on the conditions stated by WMO (2021), according to which sunshine duration is the total period where DNI exceeds  $120 \text{ W/m}^2$ . Afterward, we classified the aerosol load into clusters based on the Aerosol Optical Depth at 500nm ( $AOD_{500}$ ) as follows:

- $AOD_{500} \leq 0.05$ : Clear Sky/Low aerosol load
- $0.05 < AOD_{500} \leq 0.15$ : Moderate aerosol load
- $0.15 < AOD_{500} \leq 0.3$ : High aerosol load
- $AOD_{500} > 0.3$ : Very high aerosol load

Next, to confirm the results of the BRL verification, we performed a sensitivity analysis using the libRadtran (Emde et al., 2016; Mayer & Kylling, 2005) Radiative Transfer Model (RTM). More specifically, we compared the diffuse irradiance calculated from libRadtran with the estimations of BRL. This analysis examines the dependence of the aerosol-related discrepancy as function of Solar Zenith Angle (SZA) and latitude, considering the effect of parameters such as albedo and altitude.

To conduct aerosol parameterizations, we considered the default aerosol extinction profile (Shettle, 1989) and set asymmetry factor (gg) to 0.7, while varying the Single Scattering Albedo (SSA) and the Angstrom Exponent (AE), and defining  $AOD_{500}$  by adjusting the value of the parameter-b in Angstrom's law (Angstrom, 1929) as follows:

$$\tau_{\lambda} = b \cdot \lambda^{-a} \rightarrow AOD_{500} = b \cdot (0.5 \mu\text{m})^{-AE}$$

Table 2 illustrates the libRadtran settings used in this study.

**Table 2.** LibRadtran inputs

| Parameter                 | Input                                                                                               |
|---------------------------|-----------------------------------------------------------------------------------------------------|
| Atmospheric profile       | Mid-latitude summer (April-September)/mid-latitude winter (October - March) (Anderson et al., 1986) |
| Extraterrestrial spectrum | (Kato et al. 1999)                                                                                  |
| Surface albedo            | 0.2 / 0.8                                                                                           |
| Number of streams         | 6                                                                                                   |
| RT solver                 | sdisort (Buras et al., 2011)                                                                        |
| AE                        | 0 – 2 with step 1                                                                                   |
| SSA                       | 0.7, 0.9, 1.0                                                                                       |
| gg                        | 0.7                                                                                                 |
| Columnar ozone            | 300 DU                                                                                              |
| Water vapor               | 15 mm                                                                                               |

Finally, we assess the extent to which the uncertainty arising from the estimation of the diffuse fraction propagate into the output PV power, by comparing the energy production simulations

conducted with input both GHI and DHI, with that where we supplied only GHI as input and deployed BRL. The characteristics of the defined PV plants are provided in detail on Table 3.

**Table 3.** Input parameters defining the characteristics of the simulated PV plants

| Capacity | Mounting Approach     |                                                                  | Technology      |      |
|----------|-----------------------|------------------------------------------------------------------|-----------------|------|
| 1 kW     | Fixed                 |                                                                  | c-Si            | CdTe |
|          | Orientation:<br>south | Tilt Angle: f(latitude)<br>built-in function for<br>optimal tilt |                 |      |
|          |                       |                                                                  | 2-axis tracking |      |

### 3. Results

#### 3.1 Performance verification of the BRL from ground-based measurements

In this section, we evaluate the performance of BRL by comparing the actual diffuse fraction, defined as the ratio of DHI to GHI obtained directly from resampled to hourly BSRN ground-based measurements, with the diffuse fraction derived using BRL.

To isolate the influence of SZA from that associated with the atmospheric conditions, in Figure 3 we present the difference between the observed and the one estimated using BRL as a function of SZA. The patterns reflecting the differences under the distinct sky conditions indicate an additional dependency on SZA, which becomes apparent approximately beyond 60°. In most cases, there is an almost constant displacement with respect to  $y=0$  below 60°, as well as a negative trend when SZA exceeds this value. Izana presents a special case, as the station is located at a very high altitude, with adjacent clouds occasionally being situated at a lower elevation than the station itself. As a result, the actual diffuse irradiance experiences an additional enhancement due to the contribution of these adjacent lower-lying clouds – an effect that is not accounted for in the diffuse fraction model. Concerning the same grouped atmospheric conditions, Figure 4 illustrates the comparison between the observed and the estimated diffuse fraction for  $SZA \leq 60^\circ$ . This approach allows us to examine BRL performance after eliminating the influence of SZA, thereby providing a more comprehensive view of its reliability.

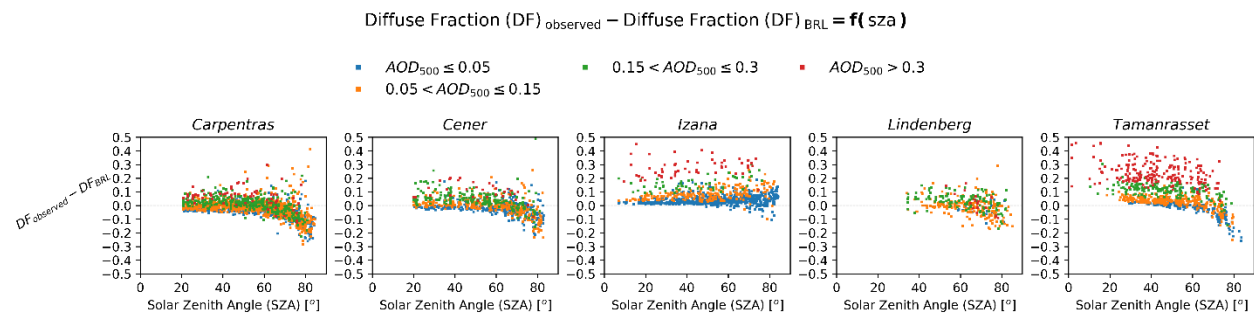


**Figure 3.** Difference between the observed and the estimated using BRL diffuse fraction as function of SZA under diverse atmospheric conditions

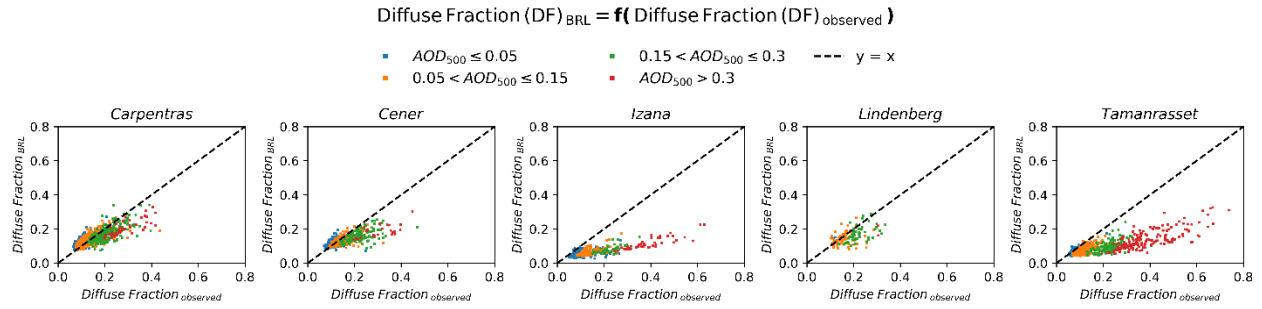


**Figure 4.** Comparison of the diffuse fraction estimated using BRL with the actual one calculated directly from the ground-based measurements under diverse atmospheric conditions

From Figures 3 and 4, a remarkable dependency of its reliability on the atmospheric conditions can be observed. Under cloud-free skies, the BRL performance relies on the atmospheric turbidity and, in particular, on the presence of aerosols. In such cases, BRL tends to underestimate, and this bias becomes more pronounced as aerosol load increases. Aiming to highlight this dependency on aerosols, Figure 5 shows the difference between the estimated and the observed diffuse fraction as function of  $AOD_{500}$ , emphasizing on also on the extent to which it is related to the aerosol type by providing  $FMF_{500}$ . A negative trend is evident across all cases, while further insights are offered regarding the composition of the aerosol scheme and its impact. Among the examined locations, in Tamanrasset and Izana, associated with the influence of Saharan dust, the coarse mode dominates, and a more distinct and well-defined curve is depicted.

It is important to clarify that we have assumed entirely cloud-free conditions. However, the criterion applied based on DNI does not fully guarantee the absence of small, scattered clouds within the sky dome. Such clouds could induce slight enhancements in DHI. A more rigorous assessment of the impact associated exclusively with aerosols could be achieved by integrating images from ground-based co-located all-sky cameras.

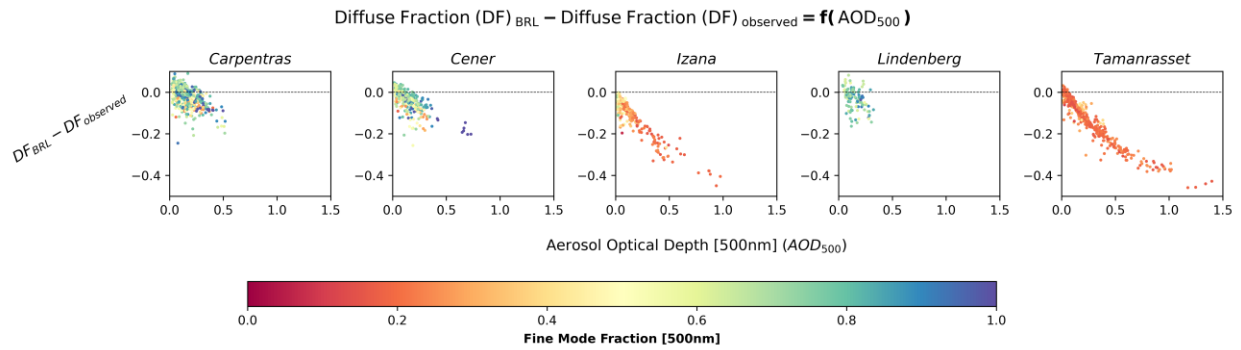


**Figure 5.** Difference between the estimated using BRL and actual diffuse fraction as function of  $AOD_{500}$  and  $FMF_{500}$

### 3.2 Sensitivity analysis of the BRL performance under cloud-free sky conditions from RT simulations

The uncertainties in estimating diffuse fraction under cloud-free sky conditions, as discussed in section 3.1, are further investigated. We performed RT simulations using libRadtran to calculate GHI and DHI under various aerosol scenarios. The resulting GHI values were then used as input to BRL to estimate the diffuse fraction, which was subsequently compared to the diffuse fraction derived directly from the ratio of DHI to GHI computed by libRadtran.

To ensure a comprehensive analysis, we considered three representative latitudes (25°, 35° and 45°). Since BRL requires an hourly time-series of GHI as input, the analysis was conducted for the summer solstice. On this day, a sufficient number of hourly values are available, corresponding to a wide range of SZA values, allowing for a robust assessment of the methodology. The sensitivity analysis was performed for surface albedo values of 0.2 and 0.8 as well as for altitudes of 0.1 and 2 km. For aerosol parameterization, we examined completely clear-sky conditions as a reference, alongside scenarios with  $AOD_{500}$  values of 0.2, 0.6, and 1, while varying the SSA and AE. Specifically, the scenarios included SSA values of 0.7, 0.9 and 1, combined with AE values of 0, 1 and 2. The results of this sensitivity analysis for an albedo of 0.2 are provided in Figure 6, while the results for an albedo of 0.8 in Figure 7.

The results presented in Figure 6 confirm that BRL performs well under clear sky conditions and for SZA below 60°, while the incorporation of aerosols in the sky scene introduces uncertainties, which will be interpreted in detail below. In all scenarios, we observe that lower values of AE correspond to higher uncertainties. Moreover, regarding SSA, when SSA is 0.9 or 1 – indicating predominantly non-absorbing or slightly absorbing particles – BRL gradually tends to underestimate the diffuse fraction as aerosol load increases. Instead, when SSA is 0.7, so the particles can be considered highly absorbing, BRL exhibits a different behavior, shifting toward an overestimation of the diffuse fraction at high aerosol loads.

The findings of this sensitivity analysis are consistent with the evaluated BRL performance from ground-based measurements presented in section 3.1 and underscore the role of aerosol in the accuracy of diffuse fraction estimations. Furthermore, concerning the impact related to AE and SSA, we confirm that the higher underestimations observed for Tamanrasset and Izana are associated with the optical properties of desert dust aerosol particles. While AE and SSA alone are not sufficient to fully characterize the aerosol type, they serve as strong indicators, aligning with the classification framework of Dubovik et al. (2002). Finally, the same comparison for albedo 0.8, provided in Figure 7, reveals a significant broadening of the discrepancies. Moreover, we observe the presence of a systematic error, even under clear sky conditions.

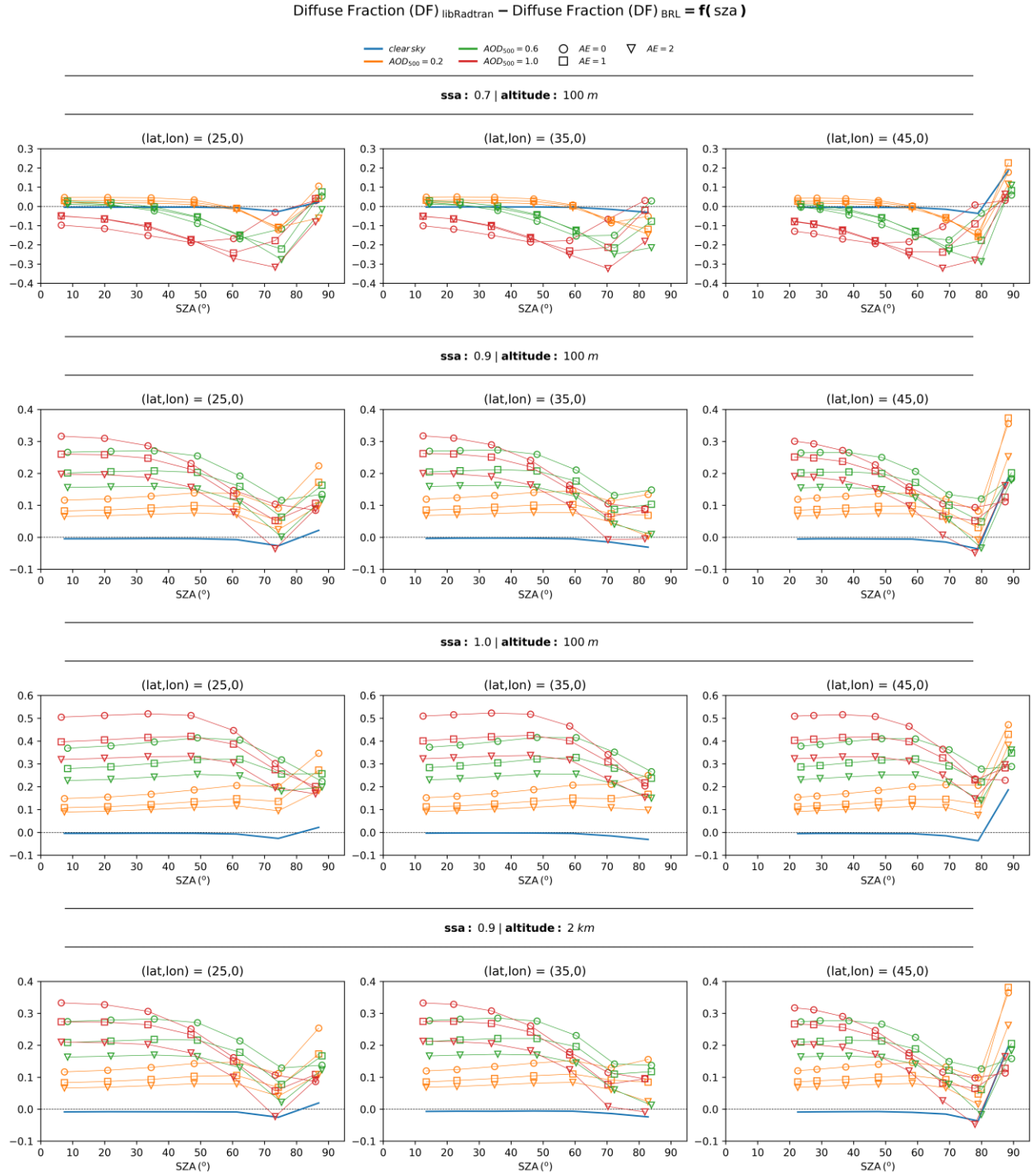


**Figure 6.** Difference between the diffuse fraction derived directly from the computations of DHI and GHI using libRadtran and the one estimated by applying BRL to the libRadtran-computed GHI for surface albedo 0.2

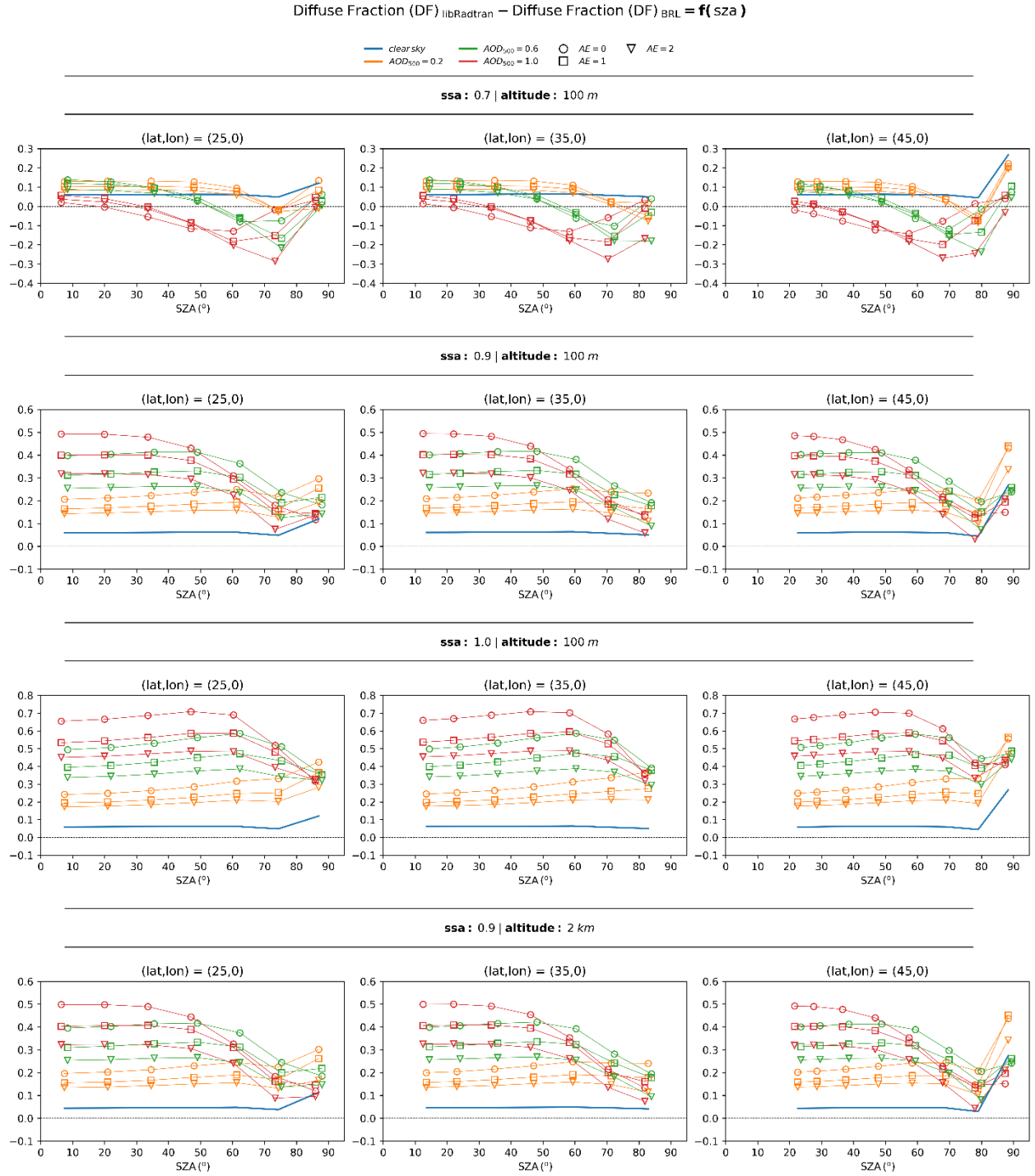


**Figure 7.** Difference between the diffuse fraction derived directly from the computations of DHI and GHI using libRadtran and the one estimated by applying BRL to the libRadtran-computed GHI for surface albedo 0.8

### 3.3 Spread of the uncertainty in the diffuse fraction estimation on the energy productions from PV systems

Uncertainties in estimating the diffuse fraction influence on the calculation of the total irradiance received by an inclined panels' surface, thereby affecting the accuracy of the PV output power simulations. In this section, we employ the main submodule of GSEE, used for modelling the electric output from a PV panel, aiming to assess the extent to which these uncertainties propagate the estimation of the hourly energy production. We analyze discrepancies arising from using only GHI as input radiation data to the model, instead of both DHI and GHI. More specifically, we compare the total energy produced per hour per unit, expressed in watt-hours (Wh), per unit of nominal power (kWp). The results of this comparison for c-Si based technology PV panels for different aerosol conditions are presented in Figure 8.

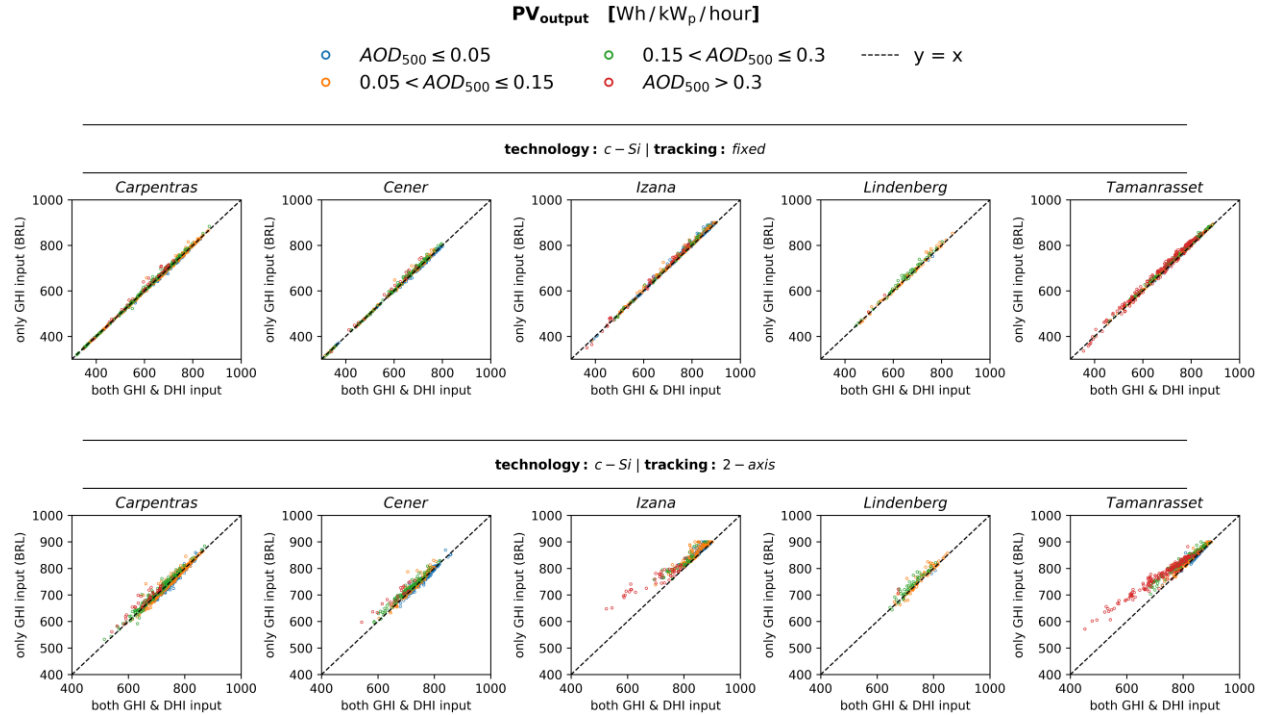


**Figure 8.** Comparison of the estimated hourly PV power generation between simulations performed using GSEE with input data consisting of either only GHI or both GHI and DHI under varying aerosol conditions

The results indicate a strong dependency of the accuracy on aerosols, which become evident within the simulations of PV plants equipped with 2-axis solar tracking system. When performing simulations without information on the radiation components leads to reduced accuracy, as the model tends to overestimate energy production. This is attributed to the contribution of aerosols, and arises from errors associated with the use of BRL.

The diffuse fraction underestimations can potentially lead to overestimations on the energy production. In the modelling of 2-axis solar tracking systems, where the panel is continuously adjusted to maintain a perpendicular orientation to incoming solar radiation, the system becomes more sensitive to uncertainties in the estimation of the diffuse fraction, leading to more significant differences in energy production. Specifically, the contribution of the direct irradiance is maximized

in such systems, as the panel exploits the entirety of the available direct irradiance. On the other hand, in the simulation of static panels, the contributions of direct and diffuse components are more evenly distributed, making the impact of diffuse fraction uncertainties less pronounced in energy production.

#### **4. Future plans**

The uncertainty regarding aerosols in estimating the diffuse fraction with BRL will be studied further. Moreover, several widely used diffuse fraction models will be also evaluated under cloud-free conditions. Furthermore, the criterion applied based on DNI does not fully guarantee the absence of small, scattered clouds within the sky dome. Such clouds could induce slight enhancements in DHI. A more rigorous future assessment of the impact associated exclusively with aerosols could be achieved by integrating images from ground-based co-located all-sky cameras. Finally, the integration of aerosol correction within the diffuse fraction models opens new possibilities for further improvements in the modelling of solar energy conversion systems.

#### **5. Linkage to Harmonia deliverables**

This study contributes to the objectives of WG3 (End user engagement towards maximizing aerosol measurement use) by using actinometric measurements of aerosol properties to improve our understanding on how aerosols affect solar energy modelling. In particular, the study addresses mainly the action deliverables “T3.2 Define the needs of stakeholders, assess the adaptation of photometry aerosol products to increase the usefulness and applicability” and “T3.3: Investigate and report on the role of aerosol uncertainty on user requirements”.

#### **6. Conclusions**

The results highlighted the uncertainties introduced by aerosols in the PV power modelling. The implementation of the BRL diffuse fraction within GSEE serves as a practical, and under certain conditions, reliable solution to the absence of detailed information for each component separately. However, its performance depends on the sky conditions.

The evaluation of the BRL performance revealed a dependency of its reliability on the prevailing sky conditions. As a result, discrepancies arising from inconsistencies in diffuse fraction estimation propagate to PV power generation. Within the modelling of PV plants equipped with 2-axis solar tracking system, the deviations are much more pronounced. More precisely, BRL demonstrates excellent under totally clear sky scenes. However, its inability to account for aerosols results in a systematic underestimation of the diffuse fraction, which becomes evident under high-loading conditions, such as during dust events.

To sum up, achieving accurate PV power simulations even under cloud-free sky conditions necessitates accounting for the influence associated with aerosols. The integration of aerosol correction within the BRL opens new possibilities for further improvements in the modelling of solar energy conversion systems.

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