

Research Article

Cross-Comparison of Ground Observations, CAMS Estimates, and Linke-Model Irradiance for Photovoltaic System Design in Sahelian Niger

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Abstract

Reliable solar-resource inputs are essential for photovoltaic (PV) and hybrid-system design, but temporal matching and measurement traceability require scrutiny where reference records are scarce. This study compares SM206-SOLAR ground observations, Copernicus Atmosphere Monitoring Service (CAMS) Radiation Service v4.6 estimates and Linke-model irradiance for Dosso, Niger, in May and August 2021. The CAMS v4.6 dataset documents the coordinates, altitude, UTC intervals and irradiation units. Ground records at nominal local observation times were paired with centered 30-minute CAMS means constructed from adjacent 15-minute intervals. Requiring both intervals to have Reliability = 1 retained 339 and 320 pairs, respectively, distributed over 31 dates in each month. Statistics were calculated across daily means formed from identical retained times in the two series. Mean ground and CAMS irradiances were 881.31 and 627.71 W m⁻² in May, and 696.29 and 530.66 W m⁻² in August. Ground-minus-CAMS mean differences were +253.59 W m⁻² (+40.40%) and +165.64 W m⁻² (+31.21%); root-mean-square differences were 268.28 and 190.73 W m⁻², with correlations of 0.620 and 0.898. Sensitivity checks using preceding or following intervals, or retaining lower-reliability intervals, did not remove the positive mean differences. Six-point Linke comparisons on 1 May and 1 August gave root-mean-square differences of 347.70 and 278.76 W m⁻². The CAMS product identity and temporal aggregation are explicitly documented, but undocumented sensor calibration and orientation, instantaneous-versus-interval sampling and limited clear-sky characterization prevent ranking the sources by accuracy. The results support qualification of irradiance inputs; they do not quantify PV-yield or system-sizing errors.

Keywords

Solar Resource Assessment, Photovoltaic System Design, CAMS Radiation Service, Ground Observation, Linke Turbidity, Irradiance Uncertainty, Sahel

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1. Introduction

Reliable solar-irradiance information underpins photovoltaic (PV) energy-yield estimation and the design of PV-based power systems. Resource assumptions enter directly into performance models [1] and subsequently inform array sizing, storage capacity, backup generation and economic assessment. This issue is particularly important in the Sahel, where ground observations are sparse and atmospheric conditions vary between dry, pre-monsoon and rainy periods [2, 3].

Satellite products help address these observational gaps. The CAMS Radiation Service combines satellite cloud information, atmospheric-composition data and radiative-transfer modelling [4, 5]. Evaluations in West Africa show that agreement with ground observations depends on atmospheric conditions and temporal scale [3]. Dust-event simulations also demonstrate the importance of representing aerosol attenuation [6]. Comparisons in Morocco and Brazil further illustrate how the ground reference, climate and aggregation interval influence the reported errors [7, 8].

Clear-sky formulations provide a complementary, but distinct, source of information. The Linke turbidity factor represents integrated atmospheric attenuation relative to a clean, dry atmosphere [9]. McClear evaluations show that physically based clear-sky estimates can agree with calibrated measurements under appropriately selected conditions [10, 11]. Such validation results cannot be transferred directly to a field record without documented calibration or to days without an objective clear-sky classification.

Developments in solar-resource assessment reinforce the need for this distinction. SARAH-3 provides a long satellite record with documented processing and validation [12], while multi-timescale evaluations in Côte d'Ivoire [13] and daily comparisons over the South Cameroon Plateau [14] show that regional performance should be assessed rather than assumed. Probabilistic work on CAMS further separates average validation scores from uncertainty at individual timestamps [15]. These studies motivate a transparent local comparison, but their accuracy estimates cannot be transferred directly to Dosso without matching instruments, quantities and temporal support.

A previous publication from the Dosso campaign examined humidity-irradiance relationships and included selected satellite-Linke comparisons [2]. The present study uses the field

observations, documented CAMS v4.6 records and a Linke-based series calculated from the measured temperature and relative-humidity records. The objectives are to quantify ground-CAMS differences after explicit temporal matching, test sensitivity to interval selection and reliability screening, compare the two sampled periods, and examine two Linke-model profiles. This is a source-consistency assessment, not a calibration study or a demonstration of optimized PV-system performance.

2. Materials and Methods

2.1. Study Site and Seasonal Periods

The experimental site is in Dosso, southwestern Niger, at approximately 13°02'30" N and 3°11'15" E, at an elevation of about 217 m. The available observations cover May 2021, a hot pre-rainy-season period, and August 2021, a humid rainy-season period. Measurements used the same site and field instrumentation. These two months provide a contrasting case study; they do not constitute a full annual record or a climatology.

2.2. Irradiance Data Sources and Quality Control

Table 1 summarizes the sources. Field observations were recorded hourly from 07:00 to 18:00 local civil time in Niger (UTC+01:00), corresponding to 06:00–17:00 UTC. CAMS Radiation Service v4.6 all-sky data were retrieved through SoDa on 20 September 2026 for 13.041667° N, 3.187500° E and 217 m [16, 17]. Both exports report 13.0417° N and 3.1875° E after header rounding. Each study month contains 2,976 consecutive 15-minute intervals, without duplicate periods or missing numeric values. The primary radiative variable is the all-sky GHI column, expressed as interval-integrated irradiation in Wh m⁻²; Clear sky GHI is not substituted. The 96 overlapping intervals on 1 August are identical in the two exports. Only these documented CAMS v4.6 records are used in the ground-CAMS comparison.

Table 1. Irradiance sources and analytical role.

Source	Nature	Resolution used	Role in this study
SM206-SOLAR	Local ground observation of global irradiance	Hourly manual observations, 07:00–18:00 local (UTC+01:00)	Local observational series
CAMS/SoDa	CAMS Radiation Service v4.6 all-sky horizontal irradiation	15-minute UTC intervals, Wh m ⁻² ; retrieved 20 September 2026	Converted to centered proxies at retained field times

Source	Nature	Resolution used	Role in this study
Linke model	Empirical irradiance calculated using vapour pressure derived from relative humidity	08: 00-18: 00 local time at 2-hour intervals; six times per date	Illustrative diurnal comparison

The field-data screening excluded nonnumeric entries and zero values inconsistent with neighbouring daytime observations. No ground value was rescaled or imputed. Of 372 scheduled entries per month, 371 numeric, positive observations remained in May and 348 in August. The two nonnumeric August entries, including a malformed decimal string, were excluded; the raw entries and cell addresses are preserved in the external supplementary file. The exports define Reliability as the proportion of reliable data in an interval. It was used as a screening flag, not as an error bar or a statistical weight.

This screening does not constitute full radiometric quality control [18]. Traceable calibration and complete sensor-orientation records remain unavailable, so the solarimeter is not treated as a reference standard. CAMS is explicitly a horizontal-plane quantity; comparability with the field measurement plane remains unverified. The CAMS exports document product identity, units and interval boundaries, but a manual instantaneous observation is not equivalent to an interval average.

2.3. Temporal Matching and Comparison Metrics

For each local observation time, one hour was subtracted to obtain UTC. Let t denote the resulting UTC time. The two complete CAMS intervals immediately before and after that instant, $[t - 15 \text{ min}, t]$ and $[t, t + 15 \text{ min}]$, were selected. Dividing each GHI irradiance by 0.25 h converts it to mean irradiance; their equal-weight average is a centered 30-minute proxy. Thus, the proxy equals twice the sum of the two irradiation values. This symmetric rule avoids arbitrarily selecting only the earlier or later interval; it is not an estimate of exact instantaneous irradiance. The primary analysis retains a pair only when both constituent intervals have Reliability = 1. Both the field observation and its CAMS counterpart are removed together when this condition fails. Daily means are then formed from exactly the same retained observation times. Equations (1)-(4) use these paired daily means, $G_{g,i}$ and $G_{c,i}$, with $n = 31$ dates per month. Positive MBE denotes ground minus CAMS, and relative bias is normalized by the matched CAMS mean, not by a known radiometric truth.

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n (G_{g,i} - G_{c,i}) \quad (1)$$

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |G_{g,i} - G_{c,i}| \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (G_{g,i} - G_{c,i})^2} \quad (3)$$

$$\text{Relative bias (\%)} = \frac{100 \times \text{MBE}}{\text{mean}(G_c)} \quad (4)$$

Each date receives equal weight in the period-level statistics, rather than weighting days by their number of observations. Pearson's r describes linear covariation, not absolute agreement; it is insensitive to a constant offset or positive rescaling. Correlations are descriptive, with no assumption of independent hourly samples or a test of the difference between monthly coefficients. Two timing checks replace the centered proxy by the preceding or following 15-minute mean while retaining the same primary pair mask. A third check retains all screened ground observations and their available centered CAMS counterparts, including lower-reliability intervals. These checks describe sensitivity to the matching and screening choices; they are not confidence intervals. Between-period changes use $100 \times (\text{August} - \text{May})/\text{May}$ for each source.

2.4. Linke-Model Calculation and Illustrative Comparison

The Linke-based irradiance series was calculated from the measured temperature and relative-humidity records. All six ground observations per date were retained and were not numerically adjusted.

For temperature T expressed numerically in degrees Celsius, the campaign's saturation-pressure approximation was used. Actual vapour pressure was calculated from relative humidity RH in percent, consistent with its definition [19]:

$$P_{vs} = 2.165 \left(1.098 + \frac{T}{100} \right)^{8.02} \text{ mmHg} \quad (5)$$

$$P_v = \frac{RH}{100} P_{vs} \quad (6)$$

The empirical turbidity coefficient $b = 0.10$ was adopted as the site-class assumption and was not fitted to the observed irradiance. The Linke factor was then evaluated with a natural logarithm and pressure in mmHg:

$$T_L = 2.4 + 14.6b + 0.4(1 + 2b) \ln\left(\frac{P_v}{1 \text{ mmHg}}\right) \quad (7)$$

Solar geometry was calculated for the corresponding UTC

instants: 08: 00-18: 00 local time at two-hour intervals maps to 07: 00-17: 00 UTC. With east-positive longitude λ , apparent solar time t_s in hours is:

$$t_s = t_{UTC} + \frac{4\lambda + E_t}{60}, t_{UTC} = t_{local} - 1 \quad (8)$$

The following campaign approximations were used: $\delta = 23.45^\circ \sin(0.986J - 80^\circ)$ and $E_t = 9.9 \sin[2(0.986J + 100)] - 7.7 \sin(0.986J - 2)$, with trigonometric arguments in degrees and E_t in minutes. Here J is day of year (121 or 213), and E_t is applied as apparent minus mean solar time; this sign convention is consistent with standard solar-position calculations [20]. For latitude ϕ , hour angle $\omega = 15^\circ(t_s - 12)$, and geometric solar elevation h :

$$\sin(h) = \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \cos(\omega) \quad (9)$$

For $s = \sin(h) > 0$, the horizontal global irradiance is the sum of the empirical direct-horizontal and diffuse terms:

$$G_L = 1370s \exp\left(\frac{-T_L}{0.9 + 9.4s}\right) + 54.8\sqrt{s} (T_L - 0.5 -$$

Table 1. Workflow of the source-consistency assessment. CAMS irradiances are converted and matched to local-time field observations before joint screening and daily aggregation. The Linke branch uses vapour pressure derived from relative humidity and solar geometry. No coefficient is fitted to force agreement.

SOURCE CONSISTENCY AT DOSSO | MAY AND AUGUST 2021

DAILY GROUND-CAMS COMPARISON

SM206-SOLAR records
+ CAMS v4.6 UTC exports

Match local/UTC times; Wh m-2 $\rightarrow$ W m-2
Centered proxy; both Reliability flags = 1

Identical times $\rightarrow$ daily means, 31 dates/month
Metrics + timing/reliability sensitivity

Interpret alongside calibration, sensor orientation, temporal support and empirical-model limitations

Implications for PV resource inputs — no PV yield or system sizing simulated

ILLUSTRATIVE LINKE CHECK

Measured temperature and humidity
+ matching ground observations

RH/100 $\rightarrow$ Pv $\rightarrow$ TL
Local time $\rightarrow$ solar elevation $\rightarrow$ irradiance

Six times per date: 1 May and 1 August
MBE, MAE, RMSE and r

The coefficients 1370 and 54.8 were used as specified in the campaign formulation in W m-2; no atmospheric coefficient was optimized. All six selected times are above the geometric horizon on both dates, including 18: 00 local time. Equations (1)-(3) were applied with the Linke model replacing G_c , i and $n = 6$. The RH value used at 10: 00 on 1 August is 73.2%, as recorded in the source dataset. Table S1 in the external supplementary file documents the inputs and calculation. Clear-sky selection [21] and independent calibration were not performed, so the comparison remains illustrative.

2.5. Analytical Workflow

Table 1 distinguishes the time-matched ground-CAMS analysis from the two-date Linke check. The former includes paired reliability screening and daily aggregation; the latter retains six observations on each selected date. Their sample sizes and purposes differ, so they are not pooled into a single validation score.

3. Results

3.1. Time-Matched Ground-CAMS Comparison

Joint screening retained 339 pairs in May and 320 in August, compared with 371 and 348 screened ground observations before the CAMS filter. All 31 dates remained in each month, with 10-11 pairs per day in May and 6-11 in August. The 60 exclusions comprise 58 available observations at 07: 00 local

time and two at 16: 00; in each case one adjacent CAMS interval has Reliability = 0.5. This is a consequence of the stated filter, not rejection based on residual magnitude. Table 2 reports statistics across the 31 daily matched-time means. These means describe the retained times, not a continuous daylight period or daily irradiation.

In May, the period averages of the daily ground and CAMS means were 881.31 and 627.71 W m⁻². MBE and MAE were both 253.59 W m⁻², relative bias was +40.40%, RMSE was 268.28 W m⁻², and r was 0.620. The ground daily means exceeded CAMS on every retained date (Figure 1). In August, the corresponding means were 696.29 and 530.66 W m⁻², with

MBE $+165.64 \text{ W m}^{-2}$ ($+31.21\%$), MAE 170.35 W m^{-2} , RMSE 190.73 W m^{-2} and $r = 0.898$ (Figure 1). The larger correlation indicates stronger daily covariation in this sample, not demonstrated absolute accuracy. The difference between MAE and MBE in August reflects residuals of both signs.

Table 2. Primary comparison of daily matched-time means. Both sources use identical times with Reliability = 1 in both adjacent CAMS intervals. Period means and metrics weight each of the 31 dates equally.

Indicator	May 2021	August 2021
Paired dates (n)	31	31
Retained observation-time pairs	339	320

Indicator	May 2021	August 2021
Pairs per date (range)	10-11	6-11
Mean ground (W m^{-2})	881.31	696.29
Mean CAMS (W m^{-2})	627.71	530.66
MBE, ground – CAMS (W m^{-2})	+253.59	+165.64
Relative bias (%)	+40.40	+31.21
MAE (W m^{-2})	253.59	170.35
RMSE (W m^{-2})	268.28	190.73
Pearson r	0.620	0.898

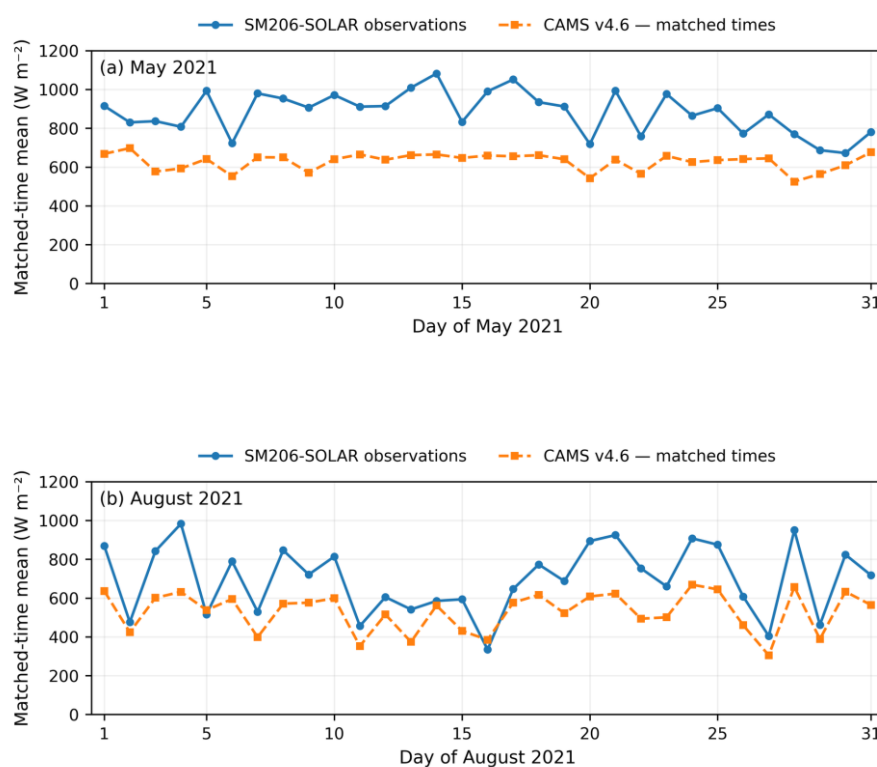


Figure 1. Daily matched-time mean irradiance in (a) May and (b) August 2021. Ground observations and centered CAMS v4.6 proxies use identical retained times after reliability screening. The panels share a vertical scale. Lines connect daily summaries; they do not represent interpolated ground measurements.

3.2. Between-Period Contrast and Sensitivity

Primary matched-time means decreased from May to August by 20.99% for the ground observations and 15.46% for CAMS (Table 2; Figure 1). On the same primary sample, using only preceding or following 15-minute CAMS intervals changes MBE by less than 0.29 W m^{-2} from the centered result in either month; RMSE ranges from 268.24 to 268.42 W m^{-2}

in May and 190.35 to 191.54 W m^{-2} in August. Retaining all 371 and 348 available ground observations without the Reliability = 1 filter gives MBE of $+242.85$ and $+159.09 \text{ W m}^{-2}$, RMSE of 257.00 and 183.03 W m^{-2} , and r of 0.621 and 0.899. Under that check, the ground means are 822.75 and 651.52 W m^{-2} because all available screened observations are included. The higher primary means therefore arise from sample selection, chiefly removal of early-morning pairs, not altered meas-

urements. All tested rules retain positive period-mean differences. Pair-level records, daily means, and sensitivity statistics are provided in the external supplementary file (Tables S2-S4). These checks do not establish an annual seasonal cycle or a calibrated resource estimate.

3.3. Illustrative Linke-Model Comparison

Table 3 and Figure 2 report the Linke-model comparisons at the six confirmed local times. On 1 May, MBE was +233.59 W m^{-2} , MAE was 283.48 W m^{-2} and RMSE was 347.70 W m^{-2} . On 1 August, MBE was +67.43 W m^{-2} , MAE was 246.67 W m^{-2} and RMSE was 278.76 W m^{-2} . Correlations were 0.791 and 0.739, respectively. Opposite-signed residuals partly cancel in the mean bias, especially in August; the lower net bias therefore does not imply close pointwise agreement. The observed agreement with the non-reference ground record should not be interpreted as calibration or validation of the

empirical model, and the six-point comparisons do not establish model accuracy.

Table 3. Ground-minus-Linke-model statistics at six local-time observations per date. The model uses vapour pressure derived from measured relative humidity and solar geometry calculated for the corresponding UTC times.

Indicator	1 May 2021	1 August 2021
MAE, ground – Linke model (W m^{-2})	283.48	246.67
RMSE (W m^{-2})	347.70	278.76
MBE (W m^{-2})	+233.59	+67.43
Pearson r	0.791	0.739

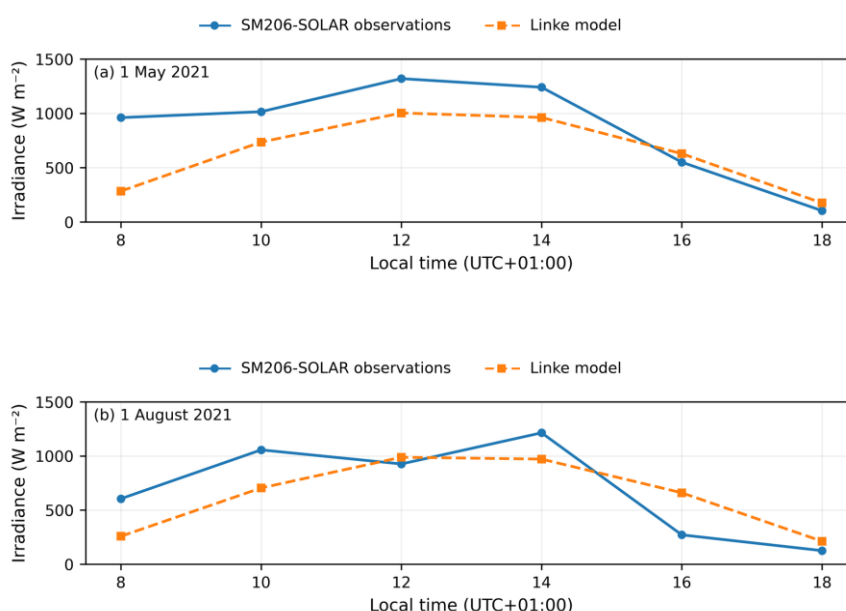


Figure 2. Ground observations and Linke-model irradiance at 08: 00, 10: 00, 12: 00, 14: 00, 16: 00 and 18: 00 local time (UTC+01: 00) on (a) 1 May and (b) 1 August 2021. All six points are retained. The panels share axis scales; connecting lines do not imply additional observations. The comparisons remain illustrative because calibration and clear-sky representativeness are unverified.

4. Discussion

4.1. Interpreting the Large Absolute Differences

The persistent separation in Table 2 and Figure 1 prevents treating the two sources as interchangeable. Earlier studies reported relatively small mean biases for CAMS-type products against calibrated measurements in Morocco and Brazil, and for McClear under clear skies in the United Arab Emirates [7,

8, 10]. Those results provide context, not an acceptance threshold for Dosso. African evaluations in Côte d'Ivoire and Cameroon also show that product performance depends on location and temporal scale [13, 14]. Comparisons across studies must account for the sign convention, reference denominator, ground instrument, irradiance component and averaging interval before numerical biases are contrasted.

Several explanations remain possible. Instrument response, calibration history and sensor orientation may affect the ground record. Product identity, UTC conversion and the

CAMS integration period are documented, and both daily series use the same retained times. Nevertheless, instantaneous field readings and centered 30-minute means have different temporal support, while missing ground values and the reliability filter change within-day sampling. Cloud variability can create genuine differences between point observations and satellite estimates [22], and dust representation affects West African irradiance calculations [6]. These contributions cannot be separated with the present records. The timing sensitivity check constrains the effect of the chosen adjacent interval; it does not eliminate sub-interval variability or establish sensor accuracy.

4.2. Interpreting the Period Contrast

Figure 1 and Table 2 show the same direction of change in the two sources between the sampled months. That correspondence is consistent with the contrasting field periods [2], but is not an independent test of radiometric accuracy. The stronger August correlation applies to this sample and aggregation rule. The persistence of positive mean differences under the sensitivity checks supports the qualitative conclusion that the series are not interchangeable; it does not establish the exact magnitude of a systematic instrument or product error. Multi-timescale evaluations [13] and probabilistic CAMS analyses [15] likewise motivate distinguishing aggregated comparison scores from uncertainty at an individual time.

4.3. Implications for Photovoltaic and Hybrid Power System Design

The +40.40% and +31.21% differences in Table 2 matter for resource selection, but are not equivalent PV-yield errors. PV models require physically compatible irradiance, temperature, orientation and loss inputs [1]. Studies using ground and CAMS data show that direct-diffuse partitioning and array configuration influence uncertainty propagation to power [23], while aerosol-dependent spectral mismatch separates broadband irradiance from module response [24]. No PV model was run here. The contribution is a documented comparison and sensitivity assessment of candidate inputs, not a numerical estimate of production, storage capacity or backup requirements.

Table 3 and Figure 2 show that Linke-model calculations differ substantially from the ground observations. This comparison is neither a calibration against the solarimeter nor a validation of the empirical model. Clear-sky selection and the fixed site-class coefficient b require independent evaluation [9, 25]. The documented CAMS records support reproducibility but do not establish clear-sky conditions on the two Linke dates. Future evaluation should first document sensor orientation and calibration and identify appropriate clear-sky periods [21], then assess the effects of qualified inputs on PV or hybrid-system performance.

4.4. Limitations and Validation Priorities

This study covers two months of one year and only two six-point Linke profiles. The ground record lacks documented calibration and complete sensor-orientation metadata. Differences between instantaneous readings and CAMS interval averages, uneven sampling and reliability screening also limit comparability; filtering does not establish accuracy. The Linke coefficient b and saturation-pressure approximation remain unvalidated at Dosso, while missing cloud and aerosol observations prevent attribution of the discrepancies. Future work should combine a calibrated, levelled pyranometer, synchronized measurements and radiometric quality control [18] with broader seasonal coverage and objective clear-sky selection [21]. These improvements would support conditional uncertainty estimates for energy-system modelling [15].

5. Conclusions

The CAMS v4.6 exports provide explicit product, unit and temporal-aggregation metadata for the Dosso comparison. With common observation-time matching and a conservative reliability filter, 339 May pairs and 320 August pairs provide 31 daily means per period. Ground-minus-CAMS MBE is +253.59 and +165.64 W m⁻², respectively, with RMSE of 268.28 and 190.73 W m⁻² and correlations of 0.620 and 0.898. Positive mean differences persist under the tested timing and reliability choices. Six-point Linke-model comparisons give RMSE of 347.70 and 278.76 W m⁻². Reproducibility of the analysis does not establish source accuracy: sensor calibration, measurement-plane compatibility, sampling support and clear-sky representativeness remain to be resolved before deriving PV-yield or system-sizing implications.

Abbreviations

CAMS	Copernicus Atmosphere Monitoring Service
MAE	Mean Absolute Error
MBE	Mean Bias Error
PV	Photovoltaic
RMSE	Root Mean Square Error
SoDa	Solar Radiation Data Portal
UTC	Coordinated Universal Time

Author Contributions

Mahamadou Hamidine: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing

Aminou Baare Ali: Data curation, Investigation, Software

Hamidou Arouna Saley: Formal Analysis, Writing – review & editing

Makinta Boukar: Supervision, Validation

Data Availability Statement

The original field records are available from the corresponding author upon reasonable request. CAMS data are accessible through the SoDa service [16]. The external supplementary file provides the supporting Linke inputs, ground-CAMS pair-level records, daily summaries, and sensitivity-analysis results used in this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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