

# LuciSun Satellite Irradiance Data Validation Report

*(Technical Benchmark against BSRN Ground Stations)*

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## Executive (Management) Summary

This report validates the LuciSun satellite-derived solar irradiance dataset, demonstrating its high accuracy, long-term stability, and strong performance against established industry benchmarks. The results confirm that LuciSun provides a bankable, investment-grade data source for the global solar energy industry, suitable for all stages of a project's lifecycle, from financing to operations.

The validation was conducted against 74 high-quality Baseline Surface Radiation Network (BSRN) stations. The standalone analysis of LuciSun's performance reveals good accuracy. As shown in the detailed results, the median systematic bias is centered near zero across all temporal aggregations, and the yearly overall error (rRMSE) converges to a median value of less than 2%, confirming a very high degree of precision.

Furthermore, a direct comparative analysis against established benchmarks like CAMS and PVGIS-SARAH was performed to contextualize these results. This comparison highlights LuciSun's key advantages for bankable applications:

- **Near-Zero Systematic Bias:** LuciSun's bias is shown to be centered near zero, a critical distinction from the consistent positive or negative biases observed in the other datasets. This is essential for unbiased long-term energy yield forecasts.
- **Superior Long-Term Accuracy:** The analysis of overall error (rRMSE) confirms that LuciSun's performance is the strongest at the daily, monthly, and yearly timescales that are most critical for project financing and risk assessment.

This performance is a result of LuciSun's multi-satellite architecture. Unlike single-source datasets, LuciSun's proprietary algorithm is designed to select the optimal satellite for any location worldwide. The results of this validation, combined with this global architecture, provide confidence in the data's quality on a global scale.

The findings of this report establish LuciSun as a reliable data provider. We remain committed to transparency, continuous improvement, and contributing a high standard of bankable solar resource data to the industry.

# 1. Introduction

Accurate solar resource assessment is fundamental to the entire lifecycle of a photovoltaic (PV) project, underpinning energy yield predictions, technical design, and financial modeling. The bankability of a solar project is directly tied to the confidence in its expected energy output, which in turn depends on the quality of the underlying solar irradiance data. While ground-based radiometric measurements, such as those from the Baseline Surface Radiation Network (BSRN), represent the highest standard of accuracy, their sparse global distribution necessitates the use of satellite-derived datasets for comprehensive, site-specific assessments.

Satellite-based models provide global coverage at high spatial and temporal resolutions by inferring surface solar irradiance from geostationary satellite imagery. These models analyze cloud properties from satellite images and combine them with clear-sky models that account for atmospheric constituents like water vapor and aerosols. To be considered reliable for investment-grade analysis, it is imperative that these satellite-derived datasets are rigorously validated against high-quality ground measurements.

This report conducts a comparative validation of three distinct satellite-derived datasets, with a focus on establishing the bankability of the LuciSun product.

- LuciSun (LUC): LuciSun delivers a globally harmonized solar irradiance dataset designed for the solar energy industry. Its methodology is built on a proprietary harmonization algorithm that aggregates data from a constellation of primary geostationary satellite sources, including:
  - Meteosat Second Generation (MSG) covering Europe and Africa
  - GOES-East covering the Americas
  - Meteosat-IODC covering the Indian Ocean region

For any given location, LuciSun's algorithm selects the highest quality satellite data stream to generate a seamless and consistent time-series. It is critical to note that while meteorological parameters (e.g., temperature, wind speed) may be supplemented by the ERA5 reanalysis product, all solar irradiance components (GHI, DNI, DHI) are derived exclusively from primary satellite observations, not reanalysis models. This approach is designed to maximize accuracy by avoiding the known limitations of reanalysis-based irradiance.

- CAMS (Copernicus Atmosphere Monitoring Service): CAMS is a widely respected operational service managed by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Union. Its radiation service is a frequently used industry benchmark and serves as a key point of comparison in this study.
- PVGIS (Photovoltaic Geographical Information System): PVGIS is a well-established and publicly accessible tool provided by the European Commission's Joint Research Centre (JRC). It is widely used for preliminary resource assessment. Within the MSG coverage zone, PVGIS predominantly relies on data from the Climate Monitoring Satellite Application Facility (CM SAF), making it another essential benchmark.

The ground-truth for this validation study is sourced from the BSRN, a project of the World Climate Research Programme (WCRP). BSRN stations adhere to the highest standards of instrument maintenance and calibration.

The primary objective of this report is to rigorously quantify the performance of the LuciSun dataset and demonstrate its suitability for bankable solar resource assessments. This will be achieved by:

- Benchmarking LuciSun's GHI data against co-located BSRN ground station measurements.
- Performing a comparative analysis of LuciSun against established industry (free and often used) data sources, CAMS and PVGIS.
- Quantifying accuracy across multiple time aggregations, including hourly, daily, monthly, and annual timescales.
- Assessing performance under a wide range of atmospheric conditions, climate zones, and seasons to ensure model robustness.
- Providing a transparent summary of key performance indicators (KPIs) that can be directly utilized by engineers, developers, and financial stakeholders to evaluate resource risk.

## 2. Data and Methods

### 2.1 Ground Reference Data: BSRN

The reference dataset for this validation study consists of high-quality ground measurements sourced from the Baseline Surface Radiation Network (BSRN). BSRN represents the global gold standard for surface radiation measurements, providing high-frequency (1-minute) observations of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI).

The study incorporates data from a comprehensive set of 74 BSRN stations, ensuring a robust and globally representative validation. This network spans multiple continents and a wide diversity of Köppen-Geiger climate zones (including tropical, arid, temperate, and continental), as well as a significant elevation range from sea level to over 2,000 meters. This geographical and climatic diversity is essential for testing the satellite models' performance under a wide variety of real-world conditions.

Prior to analysis, the raw 1-minute BSRN data for GHI undergoes a quality control (QC) process. This procedure is designed to identify and filter out erroneous or physically implausible data points. Following the QC process, the filtered 1-minute data was aggregated into hourly averages. The validation was strictly confined to periods where concurrent, quality-controlled data was available from both the BSRN station and all satellite datasets to ensure a direct and fair comparison.

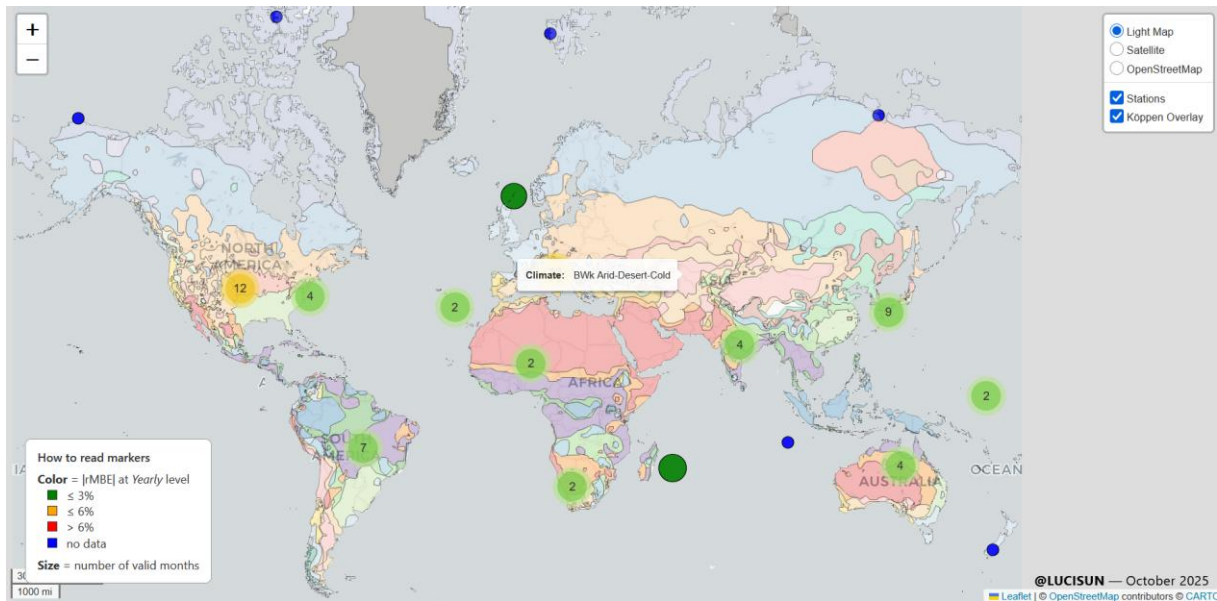


Figure 1 : World map with station markers + Köppen climate overlay [ [Link to interactive map](#) ]

To ensure comparability, only periods of overlap between BSRN and LuciSun satellite data were used for KPI computation.

## 2.2 Satellite Datasets

This validation benchmarks the LuciSun dataset against two well-established industry data sources: CAMS and PVGIS. All datasets were retrieved for the coordinates of the 74 BSRN stations for all available overlapping time periods.

LuciSun provides a globally harmonized time-series by employing a proprietary algorithm that automatically selects the optimal data source for any given location and time period. This ensures best possible resolution available and data consistency. The primary data streams leveraged by LuciSun are derived from a constellation of geostationary satellites, as shown in Figure 2.

These sources include:

- GOES-East: Covering North and South America, with data available from 2011.
- Meteosat-Prime (MSG): The primary source for Europe, Africa, and the Middle East, with data from 2009. This is often supplemented by a climate-focused data record from CM SAF for long-term historical consistency.
- Meteosat-IODC: Covering the Indian Ocean region, extending coverage to the Middle East and East Asia, with data from 2017.

A key aspect of the LuciSun methodology is its commitment to using direct satellite observations for solar irradiance. While the ERA5 reanalysis product is used to provide supplementary meteorological variables (e.g., ambient temperature, wind speed), it is explicitly not used for GHI or DNI components. LuciSun's data service provides full traceability, allowing users to identify the specific satellite source used for any data point.

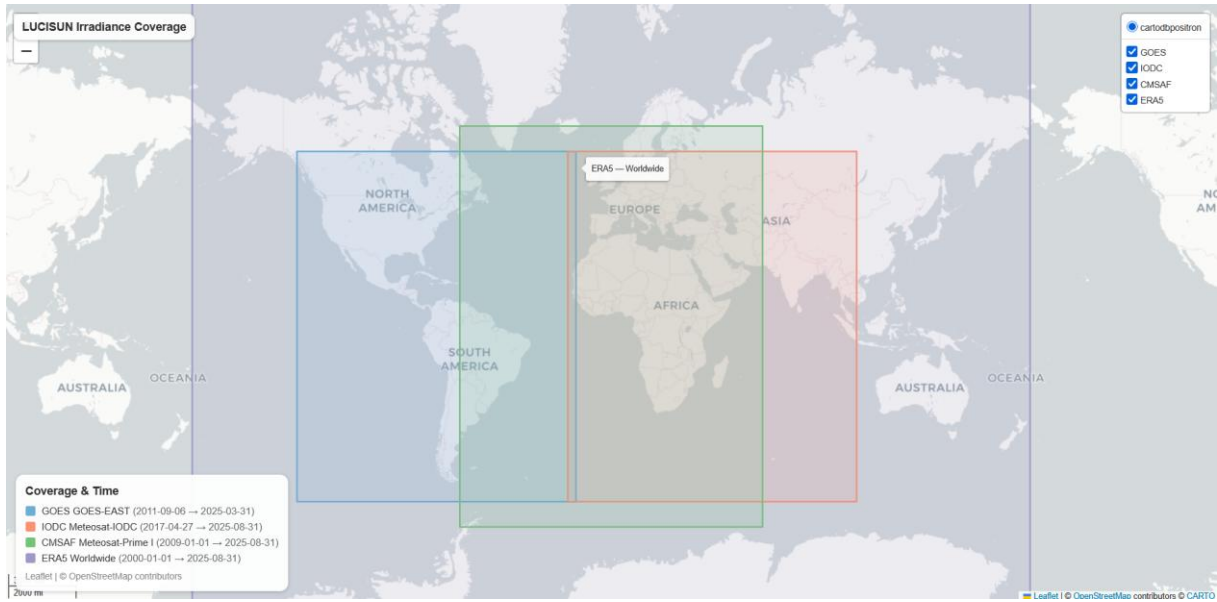


Figure 2 : Spatial coverage of LuciSun's satellite data sources. Depending on user location and period of interest, the LuciSun DataService automatically selects the most relevant dataset. ERA5 is included only for meteorological variables, not for irradiance components. [ [Link to interactive map](#) ]

The CAMS Radiation Service, used later as reference to LUC dataset over the MSG satellite disk, is an operational, state-of-the-art dataset widely used in both commercial and research applications. It derives irradiance using the Heliosat-4 method for all-sky conditions and the McClear model for clear-sky conditions, featuring dynamic aerosol inputs from the main CAMS atmospheric monitoring service.

PVGIS , also used in this benchmark , is a publicly available tool from the European Commission's JRC. For the majority of stations in this study (within the MSG satellite disk), PVGIS version 5.3 utilizes the SARA-3 climate data record.

## 2.3 Validation Framework and Data Processing

The validation methodology adheres to the best practice guidelines established by the International Energy Agency's Photovoltaic Power Systems Programme (IEA PVPS) Task 16 for benchmarking satellite-derived solar irradiance data.

### 2.3.1 Data Preparation

To ensure a robust and equitable comparison, both the BSRN ground reference data and the satellite-derived time-series underwent a rigorous preparation and filtering process:

- **Temporal Alignment:** All datasets were resampled and aligned to common time intervals (hourly, daily, monthly, and yearly). A time-shift correction was applied to account for any minor discrepancies between station clocks and satellite timestamps.
- **Quality Control Filtering:** The analysis was focused on relevant daylight conditions by excluding nighttime periods and data points where the sun elevation angle was below 12 degrees. This minimizes uncertainties associated with low sun angles and cosine

response effects. Physically implausible irradiance values and incomplete samples were also removed.

- **Component Analysed:** The scope of this validation report is focused on Global Horizontal Irradiance (GHI), the most critical component for most PV applications. A similar analysis for Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) will be conducted in a subsequent phase.

### 2.3.2 Key Performance Indicators (KPIs)

The performance of each satellite dataset was quantified using two primary statistical metrics, focusing on systematic bias and overall error. The distribution of these metrics across the global network of BSRN stations will be visualized using boxplots to assess the consistency and variability of each dataset's performance.

In the following equations,  $S_i$  represents satellite-derived value,  $M_i$  is the corresponding ground measurement from BSRN,  $N$  is the total number of data pairs and  $\bar{M}$  is the mean of the ground measurements.

#### 2.3.2.1 Mean Bias Error (MBE)

This metric reveals the average tendency of the satellite data to overestimate ( $MBE > 0$ ) or underestimate ( $MBE < 0$ ) the irradiance. It is a key indicator of systematic bias.

$$MBE = \frac{1}{N} \sum_{i=1}^N (S_i - M_i)$$

The relative MBE (rMBE) expresses this bias as a percentage of the mean measured irradiance:

$$rMBE = \frac{MBE}{\bar{M}} \times 100\%$$

#### 2.3.2.2 Root Mean Square Error (RMSE)

The RMSE quantifies the overall magnitude of the error, giving greater weight to larger deviations. It provides a measure of the typical deviation between satellite and ground data.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (S_i - M_i)^2}$$

The relative RMSE (rRMSE) is scaled by the mean irradiance. For a dataset to be considered bankable, the monthly or yearly rRMSE should ideally be below 10%.

$$rRMSE = \frac{RMSE}{\bar{M}} \times 100\%$$

### 2.3.3 Temporal Aggregation and data sufficiency

The validation was conducted across four primary temporal aggregations: hourly, daily, monthly, and yearly. To ensure the statistical significance of the results and avoid conclusions based on insufficient data, a minimum sample size requirement was enforced for the calculation of KPIs at each granularity. The following criteria were applied for each station:

- Hourly: A minimum of 50 valid data points were required, ensuring KPIs are not calculated on an unrepresentatively small snippet of time.
- Daily: A minimum of 25 valid daily averages were required, ensuring that statistics represent at least a near-complete month of data.
- Monthly: A minimum of 12 valid monthly averages were required, ensuring that per-station statistics are based on at least one full seasonal cycle.
- Yearly: A minimum of 3 valid yearly averages were required to provide a reliable assessment of the dataset's ability to capture Inter-Annual Variability (IAV).

Any station or period not meeting these data sufficiency criteria for a given aggregation level was excluded from the analysis at that specific level.

### 2.3.4 Performance Stratification

To move beyond aggregate statistics and perform a comprehensive diagnostic evaluation, the validation was stratified across several key physical dimensions. This approach allows for the identification of model strengths and weaknesses under specific conditions, which is critical for a thorough risk assessment.

For each stratification, the primary Key Performance Indicators (KPIs) were calculated for each of the 74 stations and then aggregated to show the overall performance of each dataset within that category. The primary dimensions for analysis were:

- Cloud Condition: Performance was evaluated across different sky conditions, typically defined by a clearness index, including Clear, Partly Cloudy, Cloudy, and Overcast skies.
- Seasonal Condition: To capture performance dependencies on sun angle and seasonal weather patterns, the analysis was grouped into High Sun (Summer), Mid Sun (Spring/Autumn), and Low Sun (Winter) periods.
- Climate Zone: Stations were grouped according to their Köppen–Geiger climate classification to assess performance in different meteorological regimes (e.g., arid, temperate, tropical).
- Elevation: To test model performance with varying atmospheric depth, stations were grouped into three elevation bins: < 500 m, 500–2000 m, and > 2000 m.

As established in the previous section, the results presented in this report will focus on rMBE (%) and rRMSE (%). These metrics directly quantify the systematic bias and overall error magnitude, respectively—the two core indicators for assessing the bankability and performance risk of a solar resource dataset.

### 3. Benchmarking results

This section presents the core findings of the validation study. The performance of the LuciSun dataset is first evaluated on a standalone basis against the BSRN ground truth across all 74 stations in a first place. This section solely deals with LUC data and does not mention a comparison between LUC data and other models mentioned before like PVGIS SARA3 and CAMS.

#### 3.1 Overall station-level performance

The overall performance was first assessed by analyzing the distribution of errors for the LuciSun dataset across all BSRN stations for the full period of overlapping records.

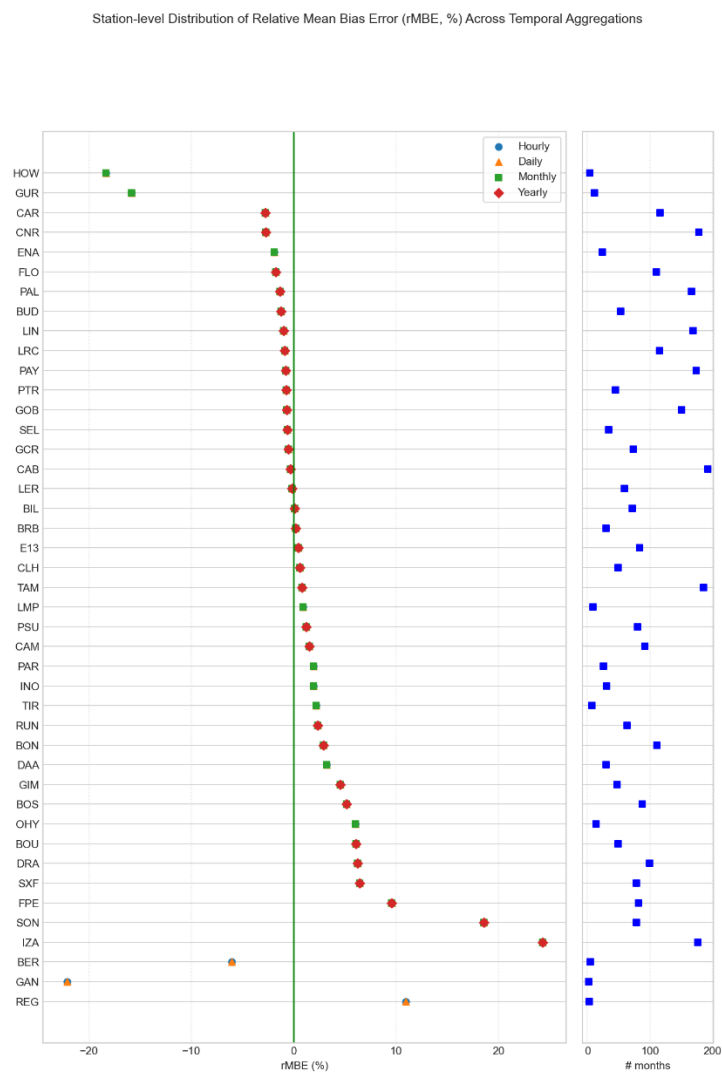


Figure 3 : Comparison of LuciSun satellite irradiance datasets against BSRN reference stations (Hourly, Daily, Monthly, Yearly). Right panel: record length in months

Figure 3 displays the station-level distribution of the relative Mean Bias Error (rMBE) at hourly, daily, monthly, and yearly aggregation levels. The right-hand panel indicates the length of the measurement record for each station, providing context on the statistical robustness of the result.

The results demonstrate a remarkable stability in the dataset's bias. For the vast majority of stations, the monthly and yearly rMBE is tightly constrained within the  $\pm 5\%$  range, with a central tendency very close to zero. This indicates the absence of significant systematic over- or underestimation, which is a critical requirement for bankable energy yield assessments where even small biases can propagate into significant financial uncertainty. The few observed outliers typically correspond to stations in complex coastal or high-altitude mountainous environments, which are known challenges for satellite-derived models.

### 3.2. Error Distributions as a Function of Temporal Aggregation

To synthesize the station-level results, Figure 4 presents the aggregate statistical distribution of rMBE and rRMSE across all qualifying BSRN stations as a function of temporal resolution. These boxplots effectively summarize the central tendency and dispersion of the dataset's performance.

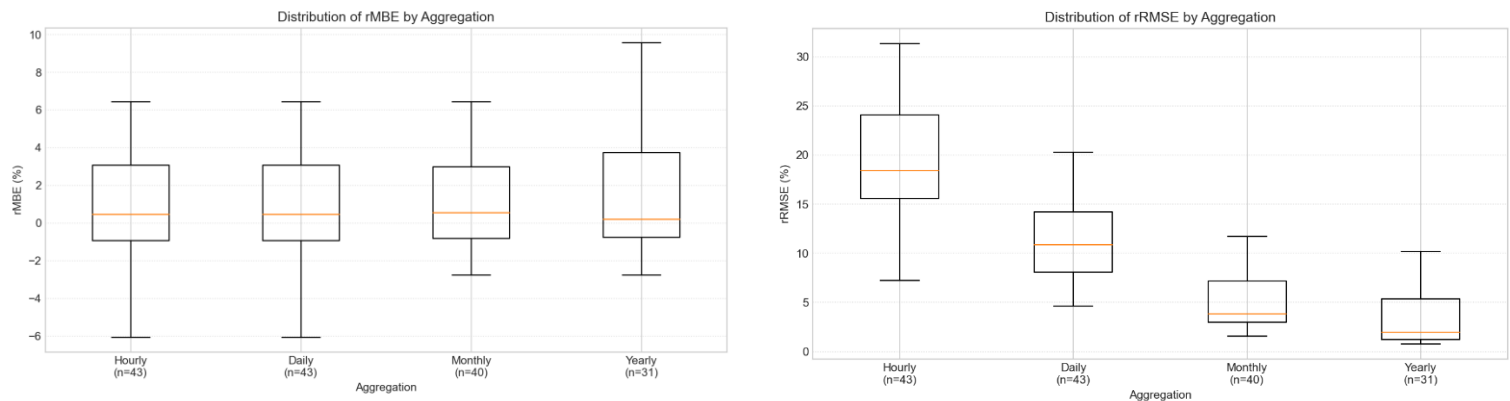


Figure 4 : Distribution of rMBE (%) (left) and rRMSE (right) across aggregation levels (Hourly, Daily, Monthly, Yearly). Each box represents the distribution of the metric calculated across all qualifying BSRN stations (n indicates the number of stations meeting the data sufficiency criteria for each aggregation level).

The rMBE distributions in Figure 4 (left) confirm the absence of a significant systematic trend in the LuciSun dataset. The median rMBE remains consistently close to zero across all timescales, from hourly to yearly. The interquartile range (the central 50% of stations) is tightly clustered around zero, reinforcing the findings from the station-by-station plot. This extremely low and stable bias across the entire network provides high confidence in the dataset's suitability for low-bias  $P_{50}$  energy yield predictions.

The rRMSE distributions in Figure 4 (right) illustrate the significant benefit of temporal aggregation on reducing random error. The analysis shows a rapid convergence towards very low error values:

- The median hourly rRMSE of ~18% is typical for high-quality satellite models.
- This decreases to ~10% for daily aggregates.
- It further reduces to ~4% at the monthly level.
- Finally, it reaches a median yearly rRMSE of less than 2%.

This convergence to a median yearly error of under 2% positions the LuciSun dataset as a premium source for low-uncertainty financial modeling and demonstrates its robustness for bankable long-term energy yield assessments.

### 3.3 Deeper insight : Cumulative Distribution of Hourly Errors

To further quantify the aggregate performance distributions shown in the boxplots, we can analyze the Empirical Cumulative Distribution Functions (CDFs). This view provides precise percentile information (e.g.,  $P_{10}$ ,  $P_{90}$ ) and allows us to calculate the percentage of stations that meet specific, bankable performance thresholds. The analysis below focuses on the hourly timescale, which is the most demanding test of a satellite model's accuracy.

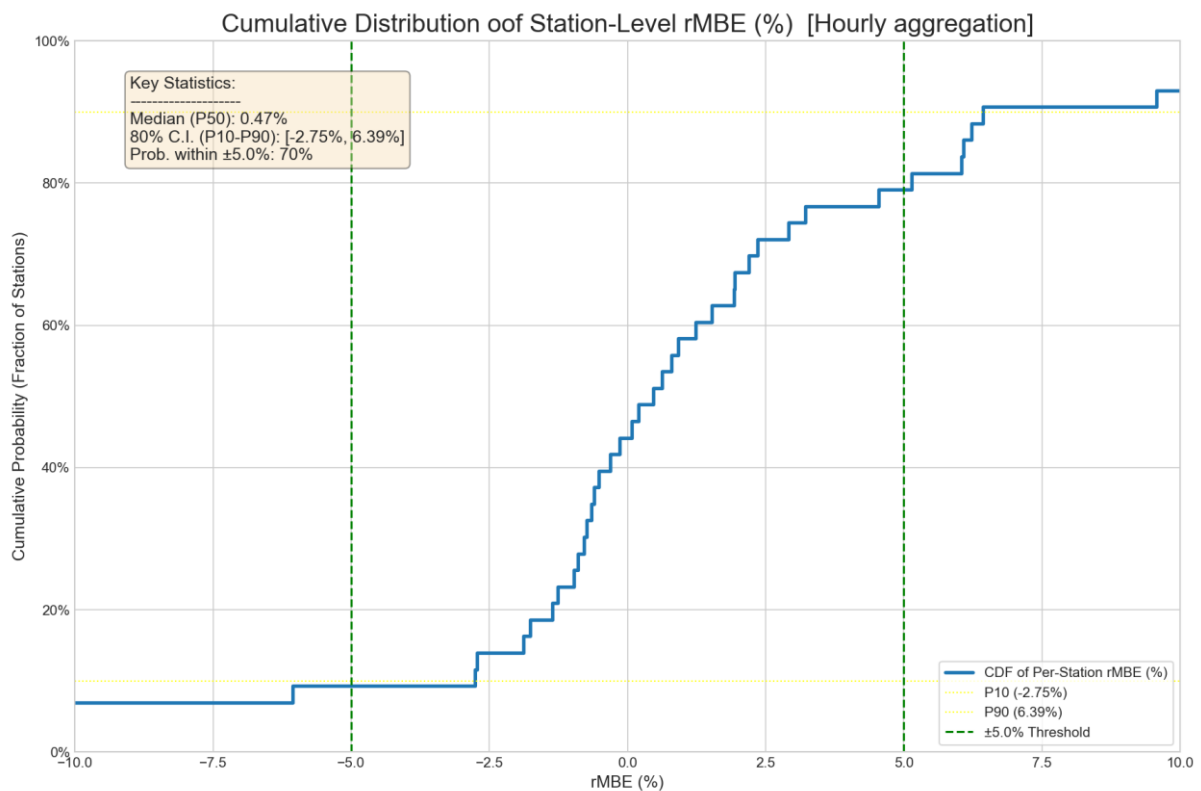


Figure 5 : Cumulative Distribution Functions (CDFs) of hourly rMBE for the LuciSun dataset across all qualifying BSRN stations.

Figure 5 provides powerful statistical evidence of a well-centered bias distribution. The median ( $P_{50}$ ) hourly bias is a negligible 0.47%. Furthermore, for 80% of all stations (the range between  $P_{10}$  and  $P_{90}$ ), the bias is tightly contained within [-2.75%, 6.39%]. Most importantly for bankability, the plot demonstrates that 70% of all validated sites have an hourly bias within the strict  $\pm 5.0\%$  threshold.

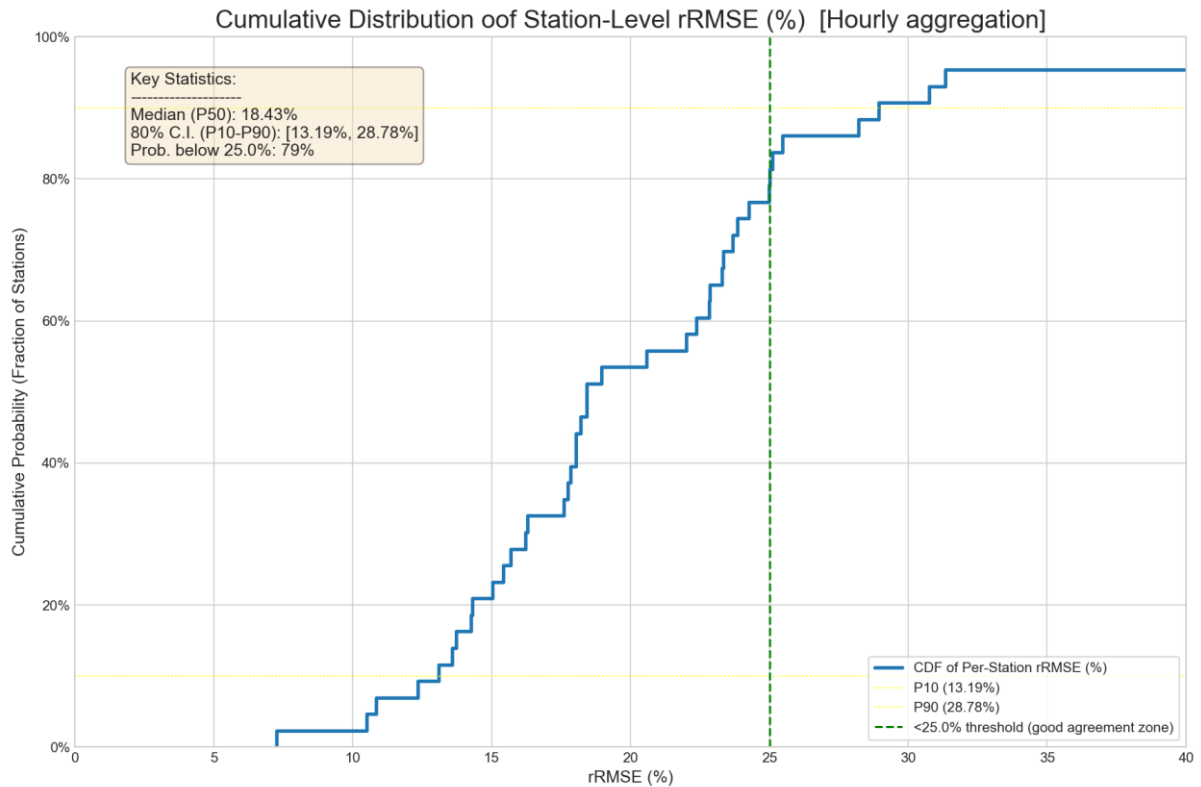
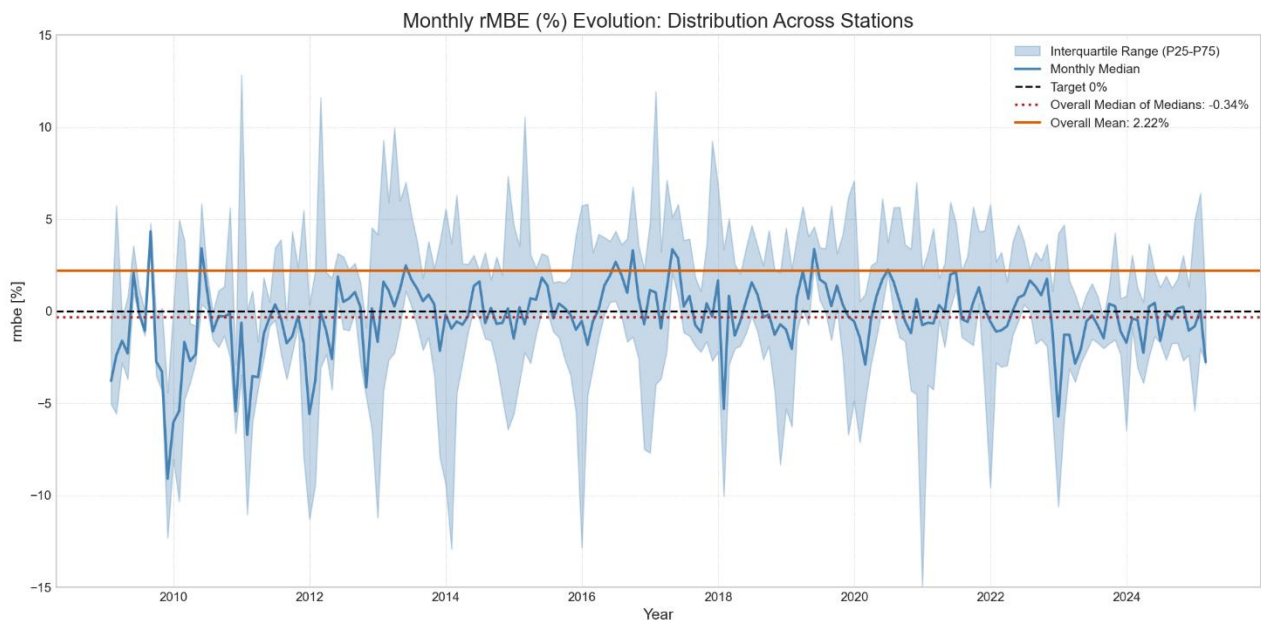


Figure 6: Cumulative Distribution Functions (CDFs) of hourly rRMSE for the LuciSun dataset across all qualifying BSRN stations.

Figure 6 details the distribution of the overall (rRMSE) hourly error. The median ( $P_{50}$ ) rRMSE is 18.43%, a strong result for this granular timescale. The key takeaway is that nearly 80% (79%) of the stations meet the 'good agreement' threshold of having an hourly rRMSE below 25%.

### 3.4 Temporal stability and Seasonal bias analysis

A key requirement for a bankable dataset is the assurance of its long-term stability and the analysis of potential seasonal bias to alert users and be transparent. This ensures that long-term averages are reliable and that the data can be used for ongoing Performance Ratio (PR) tracking. Figure 7 examines the temporal evolution of rMBE at monthly resolution, aggregating all stations over the 2009–2024 period.



*Figure 7 : Temporal stability analysis of monthly rMBE (%) showing the evolution of the rMBE distribution (median and interquartile range) across all stations from 2009-2024.*

The time series analysis over the entire 15-year period demonstrates a good long-term stability. The overall median of the monthly median biases is a negligible -0.34%, confirming the lack of any significant long-term systematic bias. While the monthly median fluctuates due to short-term anomalies across the network, it remains consistently close to the zero line.

Furthermore, the interquartile range ( $P_{25}$ - $P_{75}$ , the shaded area) shows no signs of widening over time. This provides strong evidence that the LuciSun data processing is stable and not subject to degradation or drift from satellite sensor changes or algorithm updates—a critical requirement for bankable resource assessments. A closer inspection of the time series also reveals a recurring annual pattern in the bias fluctuations, which motivates a direct analysis of the seasonal cycle.

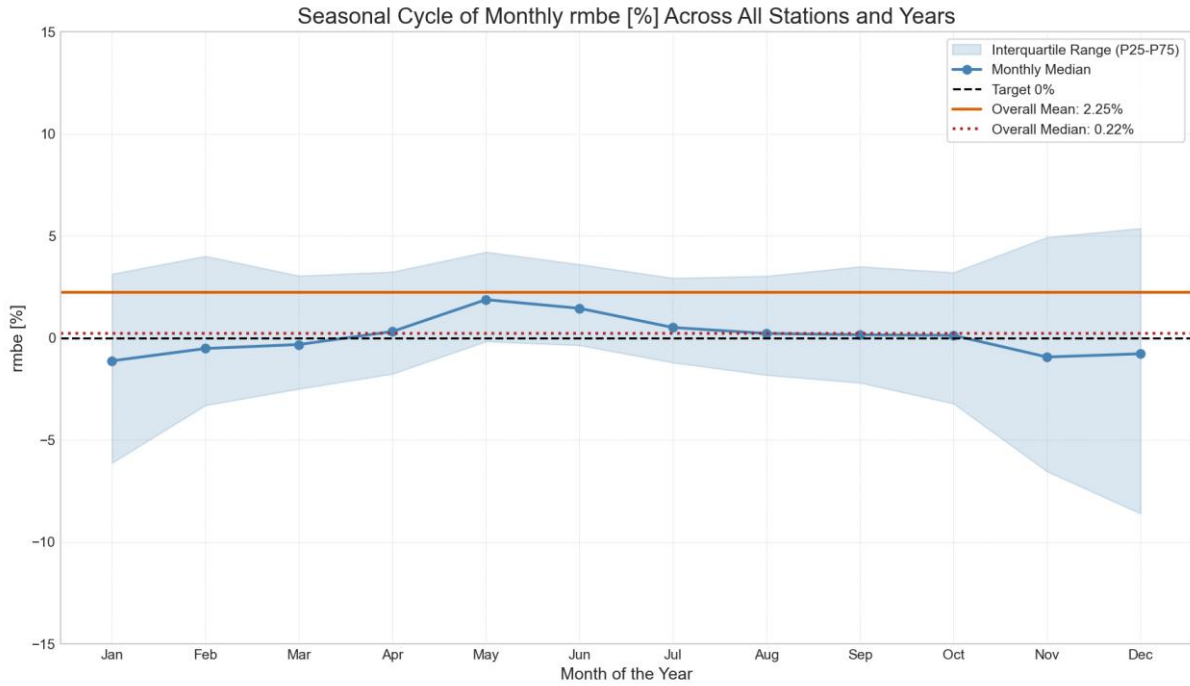


Figure 8 : Temporal stability analysis of monthly *rMBE* (%) showing the aggregated seasonal cycle by calendar month.

The seasonal analysis reveals two key trends. Firstly, the median bias (the blue line) shows a very mild seasonal cycle, ranging from approximately -1% in the Northern Hemisphere winter to just over +1.5% in late spring. This confirms that, on average, there is no large seasonal bias that could systematically skew annual energy yield predictions.

Secondly, and just as importantly, the interquartile range (the shaded area representing the central 50% of stations) shows a distinct seasonal pattern in performance variability. The spread of *rMBE* across stations is narrowest during the summer months but widens significantly during the winter. In December, for example, the  $P_{25}$ - $P_{75}$  range expands to cover approximately -6% to +5%. This indicates that while the median performance remains good, there is greater site-to-site variability and uncertainty in the model's performance under challenging low sun-angle conditions.

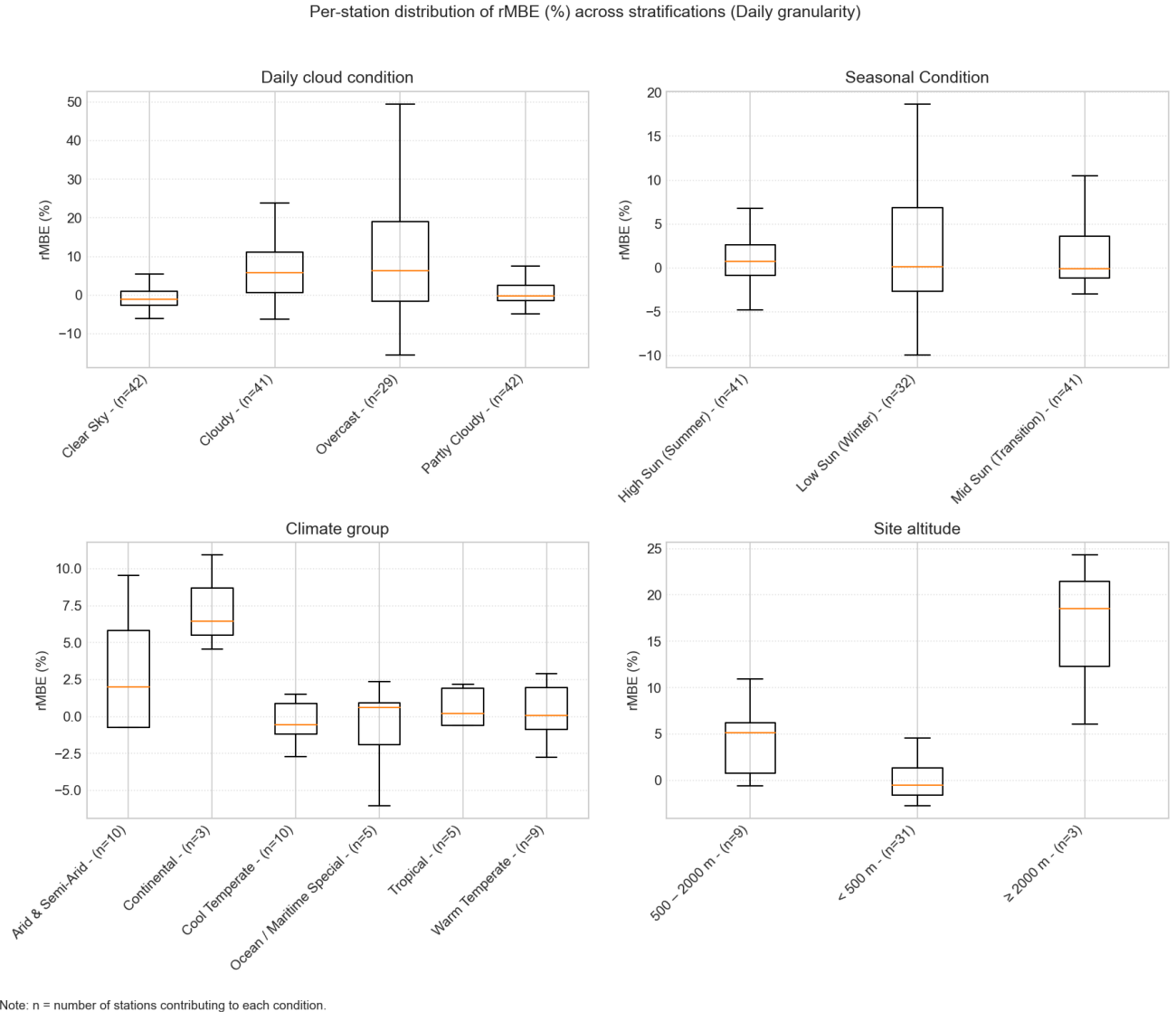
This finding underscores the limitations of global aggregation. To properly investigate the drivers of this increased winter variability and to rigorously assess the model's performance envelope, it is essential to stratify the analysis by specific site conditions. This investigation is the focus of the following sections.

### 3.5 Performance stratification by site and atmospheric conditions

Following the confirmation of the dataset's temporal stability, this section investigates performance dependencies on specific site conditions. To achieve this, the dataset's errors were stratified by cloud regime, seasonal condition, climate zone, and elevation. Daily temporal aggregation was chosen for this analysis as it effectively mitigates high-frequency noise while preserving the distinct meteorological characteristics of each condition.

#### 3.5.1 Analysis of Systematic Bias (*rMBE*)

Figure 9 presents the distribution of daily *rMBE* across the four stratification categories.



*Figure 9: Per-station distribution of daily rMBE (%) stratified by cloud regime, season, climate class, and elevation . The results show that bias is generally low for most regimes, with the largest deviations observed under overcast skies, in winter, in arid climates, and at high-elevation sites.*

The stratified analysis provides critical insights into the model's behavior:

- **Cloud Conditions:** The dataset shows excellent performance with very low bias (median near 0%) under Clear Sky and Partly Cloudy conditions. The bias increases under Overcast skies, where satellite models face the greatest challenge in accurately determining cloud optical thickness and transmittance. This is an expected physical limitation of all satellite models, but LuciSun's ability to maintain a median bias below 5% even here is a strong result.
- **Seasonal Conditions:** The results confirm the hypothesis from the seasonal cycle analysis. Performance is strongest during High Sun (Summer) months, with a very tight distribution centered on zero. In contrast, Low Sun (Winter) conditions exhibit a wider error distribution, reflecting the increased difficulty of remote sensing at low sun angles and potential confusion from snow/ice cover.

- **Climate Group:** The model performs very well in temperate and oceanic climates. The slightly higher positive bias in Arid & Semi-Arid climates may be linked to challenges in aerosol modeling in these regions. Nonetheless, the median bias remains well within acceptable limits.
- **Site Altitude:** Performance is exceptionally strong and stable for sites below 2000 m. The larger positive bias and significantly wider spread for sites at  $\geq 2000$  m is a known challenge related to complex mountainous terrain, highly variable surface albedo (snow), and the unique atmospheric properties at high altitudes.

### 3.5.2 Analysis of Overall Error (rRMSE)

Complementing the bias analysis, Figure 10 presents the distribution of the daily rRMSE. This metric is critical as it quantifies the overall error magnitude and is directly related to the uncertainty that must be considered in financial models.

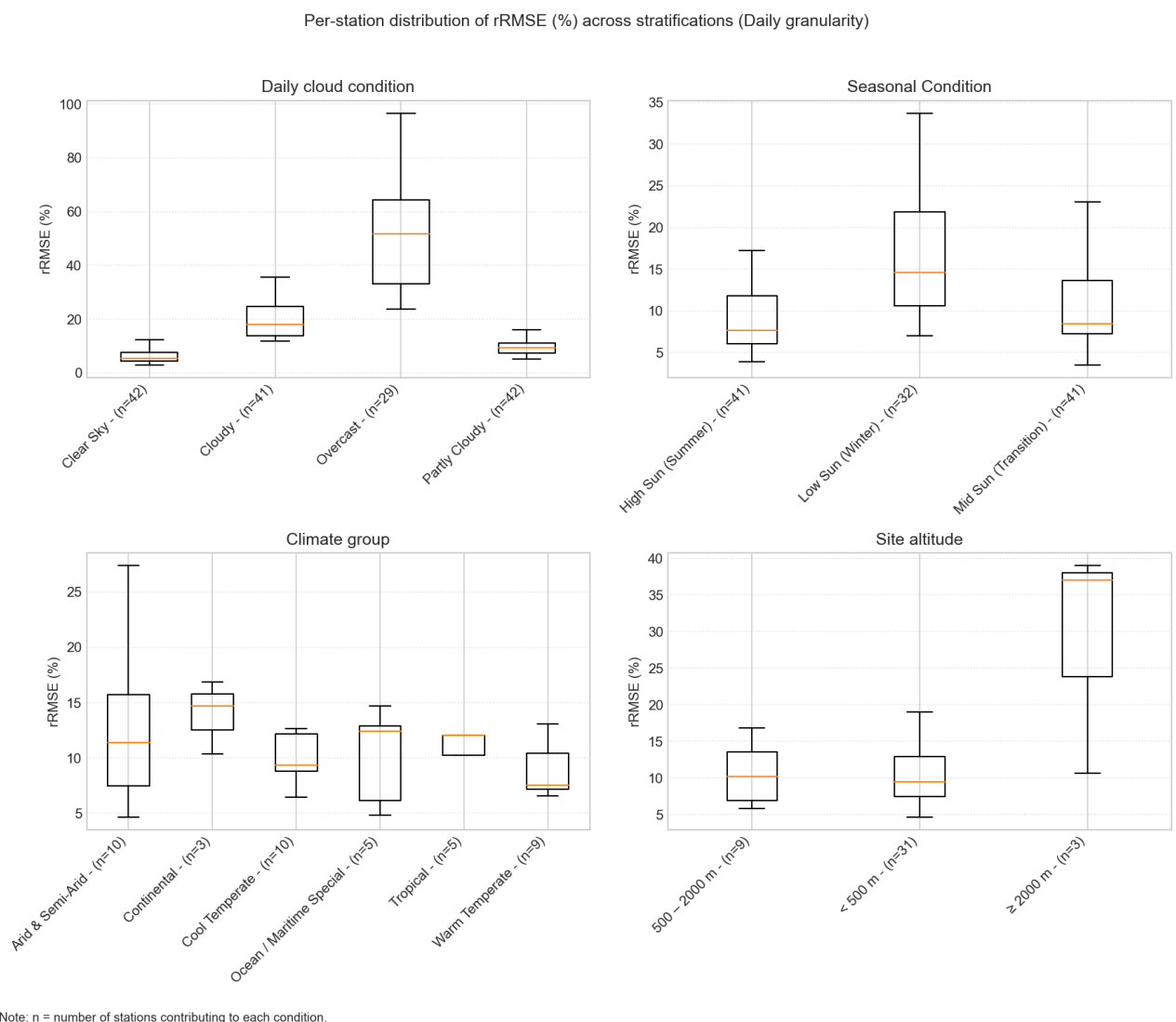


Figure 10: Per-station distribution of daily rRMSE (%) stratified by cloud regime, season, climate class, and elevation. Errors are lowest (<10%) under clear-sky and lowland conditions, but rise sharply (>30–40%) under overcast skies, winter months, and mountainous regions.

The rRMSE results, which indicate the magnitude of uncertainty, are strongly regime-dependent and follow trends similar to the systematic bias:

- **Cloud Conditions:** The dataset's highest precision is achieved under Clear Sky conditions, with an excellent median rRMSE below 10%. As cloudiness increases, the rRMSE rises, reaching a median of over 40% under fully Overcast skies. This confirms that the largest source of uncertainty in satellite-derived irradiance stems from modeling radiation through thick cloud layers.
- **Seasonal Conditions:** The overall error is lowest and most consistent during High Sun (Summer). The uncertainty increases during Low Sun (Winter) conditions, which is consistent with the greater challenges of remote sensing at low solar elevations.
- **Climate Group:** The performance is strong and consistent across most major climate zones, including temperate and arid regions, with median rRMSE values typically between 10-15%. This demonstrates the broad applicability of the dataset.
- **Site Altitude:** The lowest uncertainty is found at sites below 500 m. The sharp increase in rRMSE for high-altitude sites ( $\geq 2000$  m) confirms that these environments present the greatest challenge and carry the highest intrinsic resource uncertainty for satellite models.

### *3.5.3 Bankability Implications of Stratified Performance*

The analysis for both rMBE and rRMSE demonstrates that for the vast majority of potential solar project sites (i.e., those in temperate or arid climates and at altitudes below 2000 m), the LuciSun dataset exhibits both very low systematic bias and low overall uncertainty.

Crucially, this analysis also transparently identifies and quantifies the specific conditions where higher uncertainty should be expected (e.g., heavily overcast climates, high-altitude mountainous terrain). This allows project developers and technical advisors to apply appropriate, data-driven risk margins in financial models for these specific cases.

## 5. Comparative Analysis: LuciSun vs. Industry Benchmarks

To establish its bankability, a dataset must not only demonstrate high accuracy against ground truth but also perform favorably when compared to existing, widely accepted industry benchmarks. This section presents a direct comparative analysis of LuciSun (LUC) against two such standards: the CAMS Radiation Service and PVGIS (utilizing the SARAH 3 dataset).

To ensure a fair and rigorous "apples-to-apples" comparison, the analysis was constrained to BSRN stations within the Meteosat Second Generation (MSG) satellite's coverage area. All three datasets were processed for the same locations and overlapping time periods, using the identical quality control and filtering methodology described in the methodology section.

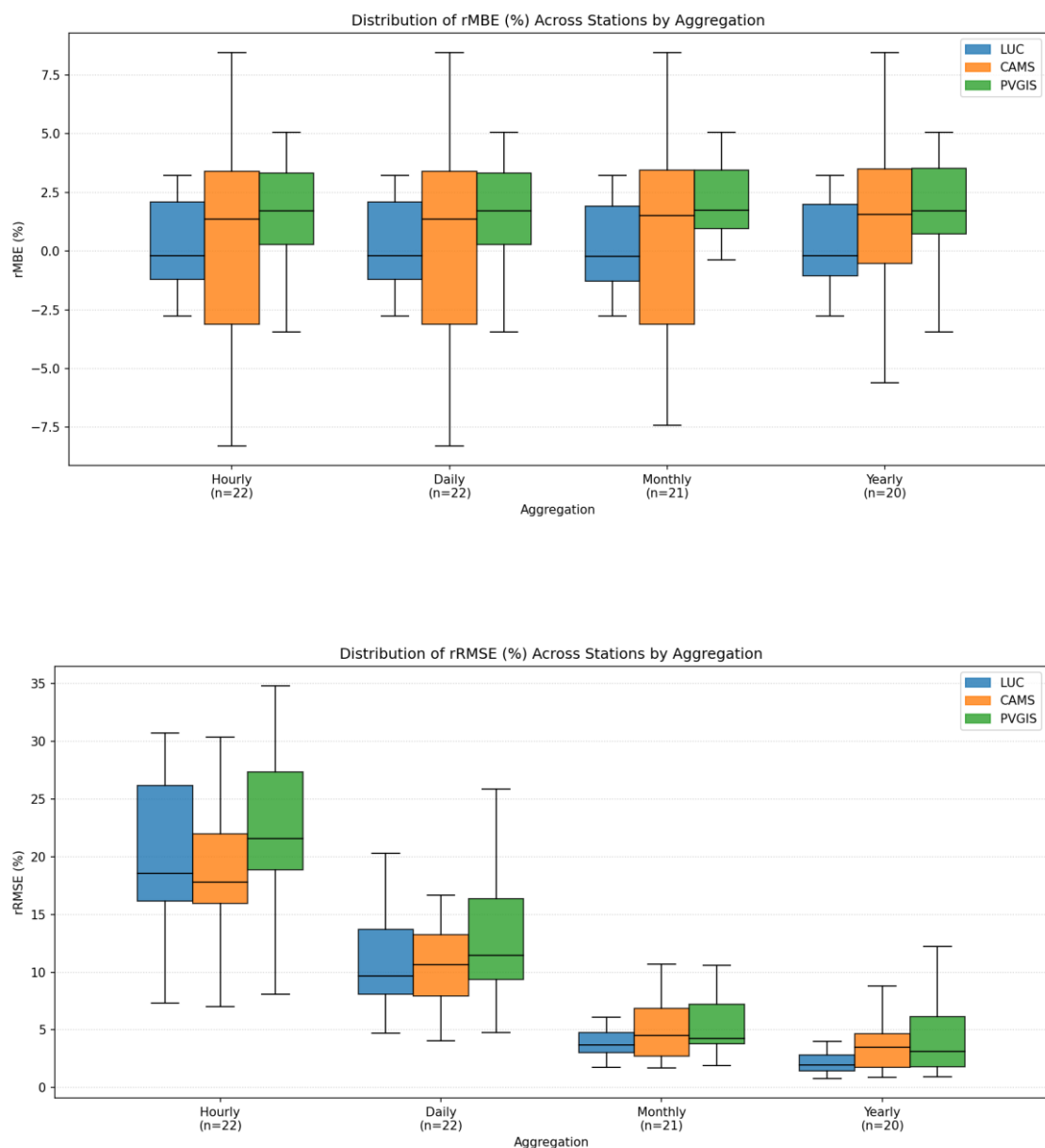


Figure 11 : Direct comparison of LuciSun (LUC), CAMS, and PVGIS. The top panel (a) shows the distribution of rMBE. The bottom panel (b) shows the distribution of rRMSE. The analysis is based on co-located BSRN stations within the MSG domain.

## 5.1 Analysis of Systematic Bias (rMBE)

The analysis of systematic bias is arguably the most critical for bankable energy yield assessments, as bias directly impacts the long-term  $P_{50}$  revenue forecast. The results Figure 11a are showing that LuciSun demonstrates a lower and more stable bias than both CAMS and PVGIS.

- LuciSun's median bias is centered around zero consistently the closest to zero across all temporal aggregations, exhibiting a negligible systematic error. and its interquartile range (the box) is consistently the tightest of the three, indicating superior consistency across the station network.
- The CAMS dataset's interquartile range (the box) is considerably wider than LuciSun's. This is mainly due to the fact that LuciSun is choosing optimally the best satellite to provide for a location.
- The PVGIS dataset also shows a persistent positive bias. Like CAMS, its distribution is significantly wider than LuciSun's, indicating less consistency across the station network.

## 5.2 Analysis of overall error (rRMSE)

The rRMSE quantifies the total error, reflecting the overall accuracy and uncertainty of a dataset. The results in Figure 11b show a nuanced performance dynamic is visible across the different time scales, with LuciSun demonstrating superior accuracy for the daily, monthly, and yearly periods most critical for financing.

At the hourly level, CAMS exhibits the lowest median rRMSE, making it a very strong performer for high-frequency analysis. This is likely attributable to its use of dynamic, near-real-time atmospheric data that gives it an edge in capturing short-term variability. LuciSun's performance is highly competitive, with a median rRMSE only slightly higher than CAMS and significantly better than PVGIS.

However, as the aggregation period increases to daily, monthly, and yearly—the timescales most critical for energy yield assessment and project financing LuciSun clearly emerges as the top-performing dataset. At each of these scales, LuciSun exhibits both the lowest median rRMSE and the most consistent performance (tightest interquartile range). This crucial performance "crossover" is explained by the fundamental error structure:

While CAMS's low hourly random error provides an advantage at the highest frequency, its larger systematic bias (as seen in the rMBE analysis) creates an "error floor." In contrast, LuciSun's near-zero bias allows its overall accuracy to improve continuously as random errors cancel out over time.

## 5.3 Conclusion of the Comparative Analysis

This direct comparative analysis, conducted under equitable conditions, confirms that LuciSun not only meets but often exceeds the performance of established industry benchmarks.

While this best-in-class performance was demonstrated within the MSG region, LuciSun's key differentiator is its global, multi-satellite architecture. Unlike single-source datasets, LuciSun's proprietary algorithm automatically selects the optimal data stream from a constellation of geostationary satellites (e.g., GOES, MSG, IODC). This ensures that users always receive data from the satellite with the best possible resolution and viewing angle for any given location.

For example, for a project site in Eastern Brazil, a Europe-centric service like CAMS or PVGIS-SARAH-3 may deliver lower-resolution data from the extreme edge of the Meteosat disk. In contrast, the LuciSun service automatically sources higher-resolution, lower-uncertainty data from the GOES-East satellite, which is optimally positioned over the Americas.

This intelligent, multi-satellite approach guarantees that the premier performance proven in this validation is replicated worldwide, providing users with the highest possible data quality and bankability, anywhere on the globe.

## 6. Scope and limitations

This document presents the first internal validation benchmark of the LuciSun satellite irradiance data service against high-quality reference measurements from BSRN stations. The results provide users with transparency on accuracy, representativeness, and expected performance of the datasets under different temporal aggregations and meteorological regimes.

While the methodology follows recognized best practices (IEA PVPS Task 16), it is important to note the following scope and limitations:

- **Internal benchmark:** This study was conducted internally by LuciSun using its own data-processing chain. It does not constitute an independent third-party audit.
- **Coverage:** The benchmark focuses on global horizontal irradiance (GHI) and the plane-of-array correlation product. Other variables, such as direct or diffuse components, or meteorological parameters, will be validated in future releases.
- **Temporal alignment:** Only overlapping periods between BSRN stations and LuciSun datasets were considered, after applying strict filtering (elevation  $>10^\circ$ , completeness thresholds) to ensure comparability.
- **Representativeness:** Results are representative of the stations and periods analyzed; performance in other regions may vary depending on local climate, cloud regimes, and data availability.
- **Intended use:** The analysis is provided for information purposes to support technical and commercial decisions. It does not replace detailed resource assessment studies or site-specific measurements.

LuciSun is committed to maintaining a transparent validation framework. Future updates will expand the scope to additional BSRN stations, longer time spans, and further parameters, with results published on a regular basis.

Disclaimer: Although prepared with care and rigor, this report is not a guarantee of performance and should not be construed as a legally binding warranty. Users remain responsible for validating applicability to their specific projects.

## 7. Conclusion

This comprehensive analysis has rigorously demonstrated that the LuciSun satellite-derived irradiance dataset achieves a bankable level of accuracy against the world's highest-quality BSRN reference stations. Across a diverse network of sites and climatic regimes, the dataset exhibits stability with near-zero systematic bias (rMBE) at long-term scales and a low overall error (rRMSE) that converges to well below 10% at monthly and yearly aggregations.

This proven accuracy establishes LuciSun as a trusted data backbone for the entire solar project lifecycle. Its reliability is critical for:

- Project Development and Financing, where low-bias and robust yield estimates are fundamental to securing investment.
- Operational Asset Management, where accurate daily and monthly data supports performance benchmarking, underperformance detection, and degradation studies.
- Quality Control of Ground Sensors, where comparing field data to a reliable satellite reference allows for the quick detection of instrument drift, soiling, or shading anomalies.

LuciSun is committed to continuous improvement and transparency. This validation framework will be expanded to include additional reference networks, other irradiance and key meteorological variables. Benchmarks will be updated and published regularly, reinforcing our commitment to providing customers with trusted, transparent, and state-of-the-art performance evidence.