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Solar Irradiance Variability and Rooftop Photovoltaic Potential at RAMS Park

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ABSTRACT

Large-scale sports facilities are energy-intensive urban infrastructures where rooftop photovoltaic (PV) applications can reduce grid dependence, yet solar resource variability at stadium-scale sites remains poorly documented. This study examines the temporal and seasonal variability of solar irradiance at RAMS Park Stadium, Istanbul, providing a preliminary, irradiance-based assessment of rooftop PV potential. Daily Global Horizontal Irradiance (GHI), Direct and Diffuse Irradiance, air temperature, and wind speed data for 2024–2025 were obtained from the NASA POWER database and analysed in R using descriptive statistics, seasonal comparisons, moving averages, the Mann–Kendall trend test, Sen's slope estimation, Seasonal-Trend Decomposition (STL), and irradiance-variability indicators. Results revealed a pronounced seasonal pattern, with higher, more stable GHI in summer and lower, more variable values in winter; mean daily GHI was approximately 4.15 kWh/m²/day, and neither the Mann–Kendall test nor Sen's slope detected a significant trend over the two-year period, while STL confirmed the dominance of the seasonal component. These findings indicate a favourable seasonal irradiance profile for preliminary rooftop PV planning, particularly in summer, although results should be interpreted strictly as an irradiance-based resource assessment rather than a complete PV performance or reliability evaluation, offering a reproducible baseline for future stadium-scale solar feasibility research.

Keywords Solar irradiance; Rooftop PV; GHI; Time-series; Stadium; NASA POWER

1. INTRODUCTION

Large-scale sports facilities are energy-intensive urban infrastructures because of their lighting, ventilation, cooling, heating, broadcasting, security, and event-related operational requirements. In recent years, rooftop photovoltaic (PV) applications have become an increasingly relevant strategy for reducing grid dependence and supporting sustainability-oriented energy planning in large public buildings. Urban rooftops are widely considered suitable spaces for distributed solar energy generation because they allow electricity production close to consumption points and reduce the need for additional land use. However, the assessment of rooftop PV potential is a multi-stage process that requires not only information on the available roof area but also the evaluation of local solar resource conditions, meteorological variability, roof geometry, shading, system efficiency, and economic feasibility. Recent studies have emphasized that solar irradiance, air temperature, wind speed, roof orientation, module efficiency, and performance losses are among the key parameters that influence rooftop PV potential and system planning (Bernasconi & Guariso, 2021; Fakhraian et al., 2021). Therefore, before conducting a complete PV system design or investment analysis, a site-specific assessment of solar irradiance variability provides an important preliminary basis for understanding the suitability of a facility for rooftop PV applications.

Global Horizontal Irradiance (GHI) is one of the most frequently used indicators for evaluating solar resource availability, especially in early-stage PV potential assessments. In addition to GHI, direct irradiance, diffuse irradiance, air temperature, and wind speed provide useful contextual information for interpreting local atmospheric conditions and their possible implications for PV planning. Previous studies have shown that solar irradiance is strongly affected by seasonal cycles, cloud cover, aerosols, humidity, and solar elevation angle, leading to short-term fluctuations and seasonal differences in potential energy availability (Liu et al., 2022). In addition, the accuracy and interpretation of satellite-based or reanalysis irradiance datasets should be considered carefully. For example, Araújo et al. (2024) compared global horizontal irradiance datasets with ground-based measurements and emphasized the

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importance of validating reanalysis-based GHI data when they are used for solar resource assessment. Similar time-series approaches, including descriptive statistics, moving averages, trend tests, and seasonal decomposition, have been used to examine solar radiation variability and to support renewable energy planning. Nevertheless, the use of such analyses should be carefully distinguished from complete PV performance or operational reliability assessments, which require additional system-specific information such as installed capacity, module characteristics, inverter losses, shading effects, degradation, monitored electricity generation, maintenance records, and failure data.

Although rooftop PV potential has been widely studied in urban buildings, relatively limited attention has been given to large-scale sports facilities such as stadiums; one of the few exceptions, a remote-sensing and GIS-based assessment of a US university campus, explicitly identified a stadium roof among the candidate structures for solar deployment (Stack & Narine, 2022). Stadiums are important candidates for rooftop PV planning because they have large roof surfaces and substantial event-based electricity demand. However, their architectural form, roof geometry, surrounding urban environment, and seasonal operating patterns make site-specific preliminary evaluation necessary. In this regard, RAMS Park Stadium in Istanbul provides a relevant application area for examining solar irradiance variability at the scale of a large sports facility. The present study uses daily NASA POWER data for the 2024–2025 period to analyse the temporal and seasonal characteristics of solar irradiance at the RAMS Park location. The analysis includes Global Horizontal Irradiance (GHI), direct irradiance, diffuse irradiance, 2-m air temperature, and 10-m wind speed.

Based on this framework, the aim of this study is to provide an irradiance-based preliminary assessment of rooftop PV potential at RAMS Park Stadium. Descriptive statistics, seasonal comparisons, moving averages, the Mann–Kendall trend test, Sen's slope estimation, Seasonal-Trend Decomposition using Loess (STL), and irradiance variability indicators such as the coefficient of variation, interquartile range, low/high irradiance day ratios, absolute day-to-day change, and run-length analysis were applied. Unlike a complete PV performance, risk, or operational reliability assessment, this study does not model an installed PV system or evaluate monitored electricity production. Instead, it focuses on solar resource variability, seasonal availability, and short-term irradiance continuity as preliminary indicators that may inform future rooftop PV feasibility studies, system design simulations, and investment planning for large-scale sports facilities.

2. Materials and Methods

2.1 Research Model

The present study employed a quantitative and descriptive time-series design to examine the temporal and seasonal variability of solar irradiance at RAMS Park Stadium in Istanbul. This design is appropriate for analysing daily solar radiation patterns, identifying seasonal components, and evaluating short-term variability in solar resource availability. Time-series approaches are widely used in solar energy studies because solar irradiance is affected by seasonal cycles, atmospheric variability, cloud cover, and local meteorological conditions (Box et al., 2015; Liu et al., 2022).

The study provides an irradiance-based preliminary assessment of rooftop PV potential for a large-scale sports facility. Rather than modelling an installed PV system or evaluating operational reliability, the analysis focuses on solar resource availability, seasonal distribution, short-term variability, and the continuity of low- and high-irradiance periods. This distinction is important because complete rooftop PV potential and performance assessments require additional parameters such as roof geometry, available roof area, module efficiency, inverter losses, shading effects, system degradation, economic conditions, and monitored electricity production (Bernasconi & Guariso, 2021; Fakhraian et al., 2021).

2.2 Study Area

The study area was RAMS Park Stadium, located in Istanbul, Türkiye. RAMS Park is a large-scale urban sports facility with a substantial roof structure and event-based operational energy demand. Its location in a densely urbanised metropolitan area makes it a relevant application site for examining the preliminary rooftop PV potential of stadium-scale facilities. In urban PV studies, site-specific assessments are necessary because solar resource availability and

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PV feasibility may vary according to local meteorological conditions, roof characteristics, surrounding urban morphology, and shading conditions (Bernasconi & Guariso, 2021; Fakhraian et al., 2021). The geographic location of the study site is shown in Figure 10.

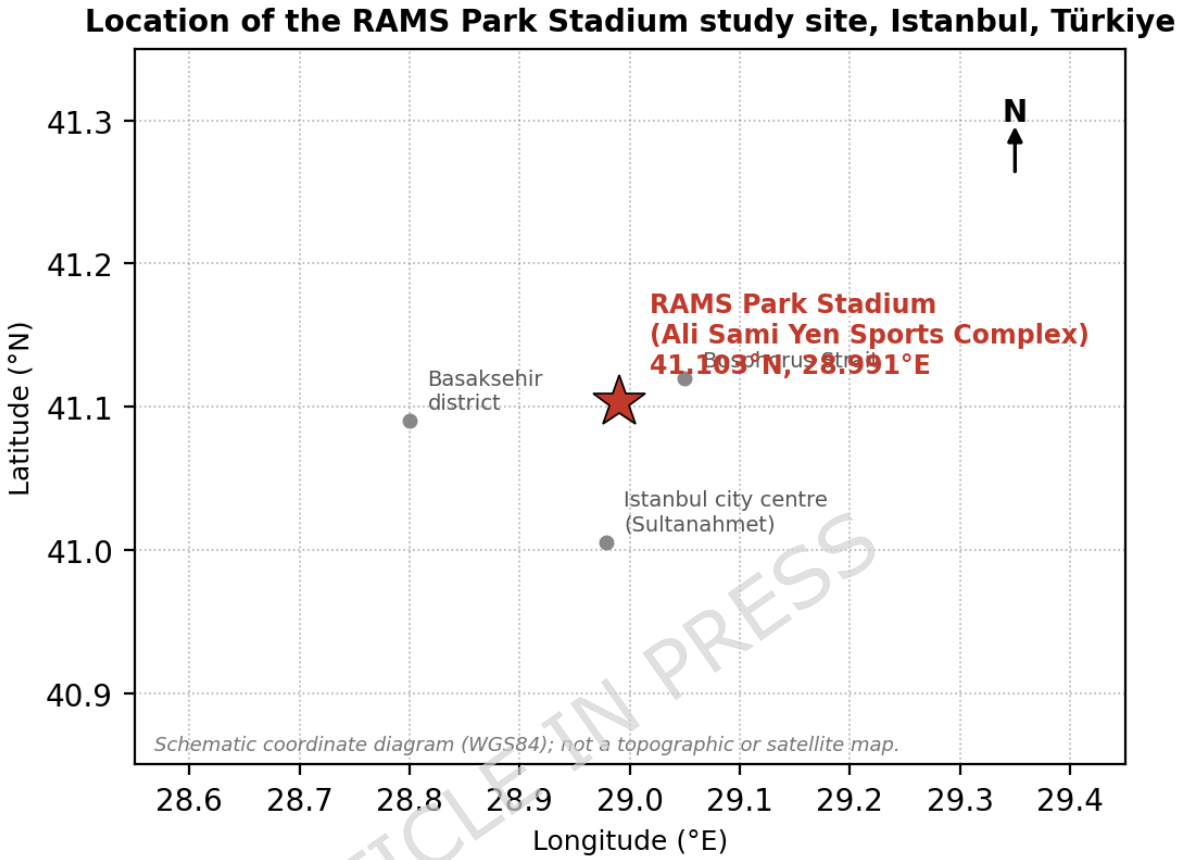


Figure 10. Location of the RAMS Park Stadium study site (41.103°N, 28.991°E), Sarıyer, Istanbul, Türkiye. Coordinates verified against publicly documented stadium records. This is a schematic coordinate diagram (WGS84 graticule with reference points for orientation) and not a topographic or satellite map; a georeferenced aerial image or on-site photograph can be substituted if the authors provide one.

2.3 Data Collection and Processing

Daily data for the period between 1 January 2024 and 29 December 2025 were obtained from the NASA POWER database(NASA, n.d.) . The dataset included Global Horizontal Irradiance (GHI), Direct Irradiance (DIR), Diffuse Irradiance (DHI), 2-m air temperature, and 10-m wind speed. These variables were selected because they represent the main solar resource and meteorological conditions relevant to preliminary rooftop PV planning. GHI was used as the primary indicator of solar resource availability, while DIR and DHI were used to describe the direct and diffuse components of solar radiation. Air temperature and wind speed were included as contextual meteorological variables because site-specific meteorological conditions are known to influence PV planning and potential assessments (Bernasconi & Guariso, 2021).

NASA POWER and other satellite-based or reanalysis products are frequently used in solar energy studies, particularly when long-term or location-specific ground measurements are not available. However, the interpretation of such datasets requires caution because reanalysis-based irradiance values may differ from ground-based observations depending on location, temporal resolution, atmospheric conditions, and data product characteristics (Araújo et al.,

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2024; Esposito et al., 2024). Therefore, in the present study, NASA POWER data were used to support an irradiance-based preliminary resource assessment rather than to represent direct measurements from an installed PV system.

After downloading the dataset in Excel format, data cleaning and processing were conducted using the R programming language (R Core Team, 2024). The date variable was converted into a standard date format, and all irradiance and meteorological variables were converted into numerical format. Missing, undefined, or infinite observations were checked and removed where necessary. A complete daily calendar sequence was generated to identify any missing dates, and the final dataset was sorted chronologically. The cleaned dataset consisted of 729 valid daily observations.

As the study used only open-access secondary meteorological data and did not involve human participants, animal subjects, or personal data, ethics committee approval was not required.

The variables used in the analysis are presented in Table 1. GHI, DIR, and DHI were expressed in kWh/m²/day, air temperature was expressed in °C, and wind speed was expressed in m/s. GHI represents the total shortwave solar radiation received on a horizontal surface, while DIR and DHI describe the direct and diffuse components of solar radiation. These variables were used to characterise the solar resource conditions and meteorological context of the RAMS Park location (Liu et al., 2022).

Table 1. Variables used in the study

Variable	Description	Unit
GHI	Global horizontal irradiance (All-sky surface shortwave downward irradiance)	kWh/m²/day
DIR	Direct short-wave radiation component	kWh/m²/day
DHI	Diffuse short-wave radiation component	kWh/m²/day
Temp	Air temperature at a height of 2 metres	°C
Wind	Wind speed at a height of 10 metres	m/s
DATE	Daily time stamp	YYYY-MM-DD

Note. Author-generated table based on variables obtained from the NASA POWER database.

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2.4 Data Analysis

The data analysis was conducted using the R programming language (R Core Team, 2024). First, descriptive statistics were calculated to summarise the general distribution of daily Global Horizontal Irradiance (GHI), including the mean, standard deviation, median, percentiles, coefficient of variation (CV), and interquartile range (IQR). These indicators were used to describe the central tendency, dispersion, and relative variability of the solar resource at the RAMS Park location. Descriptive and distribution-based indicators are commonly used in solar irradiance studies to characterise the variability and availability of solar energy resources (Box et al., 2015; Liu et al., 2022).

Seasonal comparisons were then performed by grouping daily observations into winter, spring, summer, and autumn. This step was used to evaluate the seasonal distribution of GHI and to identify periods with higher or lower solar resource availability. Since solar irradiance is strongly affected by seasonal cycles, cloud cover, atmospheric conditions, and solar elevation angle, seasonal analysis provides an important basis for preliminary rooftop PV planning (Bernasconi & Guariso, 2021; Fakhraian et al., 2021).

To examine temporal patterns, moving averages were calculated using 7-day and 30-day windows. The 7-day moving average was used to represent short-term fluctuations, whereas the 30-day moving average was used to smooth daily variability and highlight broader temporal patterns. In addition, Seasonal-Trend Decomposition using Loess (STL) was applied to separate the observed GHI series into seasonal, trend, and remainder components. STL is a widely used decomposition method for time-series data with strong seasonal structures (Cleveland et al., 1990; Box et al., 2015).

The Mann–Kendall trend test and Sen's slope estimation were applied to examine whether the GHI series showed a statistically significant monotonic trend during the analysed period. The Mann–Kendall test is a non-parametric method widely used in hydroclimatological and solar radiation time-series studies because it does not require the

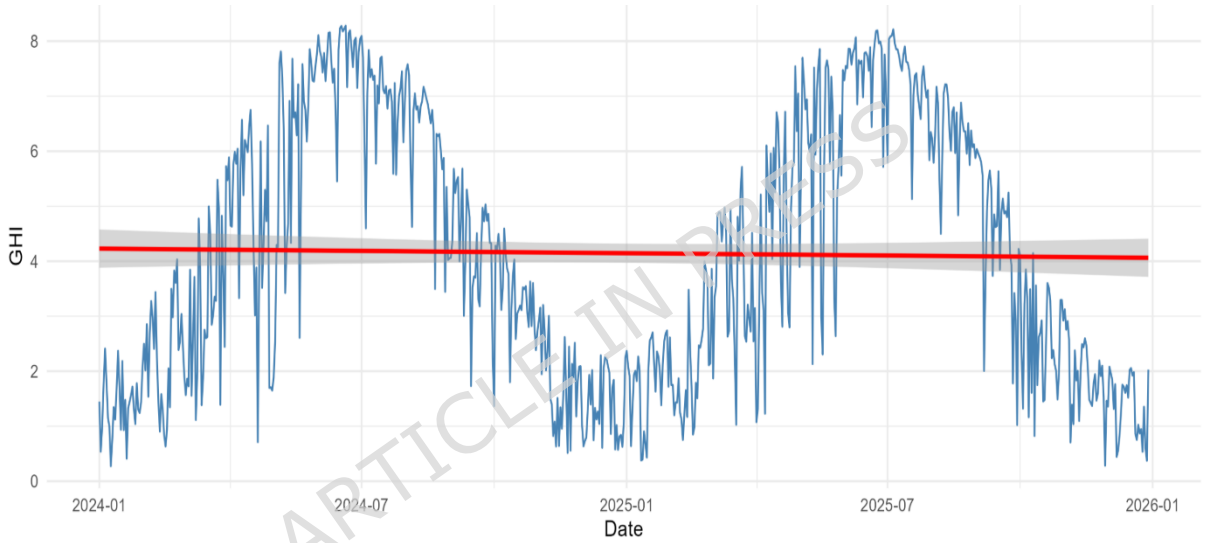
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assumption of normality (Mann, 1945; Kendall, 1975; Alashan, 2020). Sen's slope was used to estimate the magnitude and direction of the trend (Sen, 1968). However, because the dataset covers only the 2024–2025 period, the trend results were interpreted as short-period temporal behaviour rather than long-term climatic trends.

In addition to descriptive and trend analyses, irradiance variability indicators were calculated. The coefficient of variation was used to assess relative variability in daily GHI values, while the interquartile range was used to describe the spread of the middle 50% of observations. Low-irradiance days were defined as days with GHI below 1 kWh/m²/day. This threshold was used only as a descriptive indicator of very low solar resource availability and should not be interpreted as a technical minimum production threshold for a specific PV system. High-irradiance days were defined using the upper quartile of the observed GHI distribution. This data-driven threshold was used to identify comparatively favourable solar resource conditions within the analysed dataset.

Finally, absolute day-to-day GHI changes were calculated to represent short-term irradiance volatility. Run-length analysis was applied to identify the duration of consecutive low- and high-irradiance periods. These indicators were used to describe the continuity of solar resource availability, not to measure the operational reliability of an installed PV system.

3. Results



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Figure 1. Daily GHI time series at RAMS Park Stadium

Figure 1 presents the daily Global Horizontal Irradiance (GHI) time series for the RAMS Park location during the 2024–2025 period. The series shows a clear annual cycle, with GHI values increasing during spring and summer and decreasing during autumn and winter. Short-term decreases observed within the series may be associated with temporary atmospheric conditions such as cloud cover, humidity, and aerosol-related scattering. Therefore, the figure provides evidence of seasonal solar resource variability rather than direct PV system performance.

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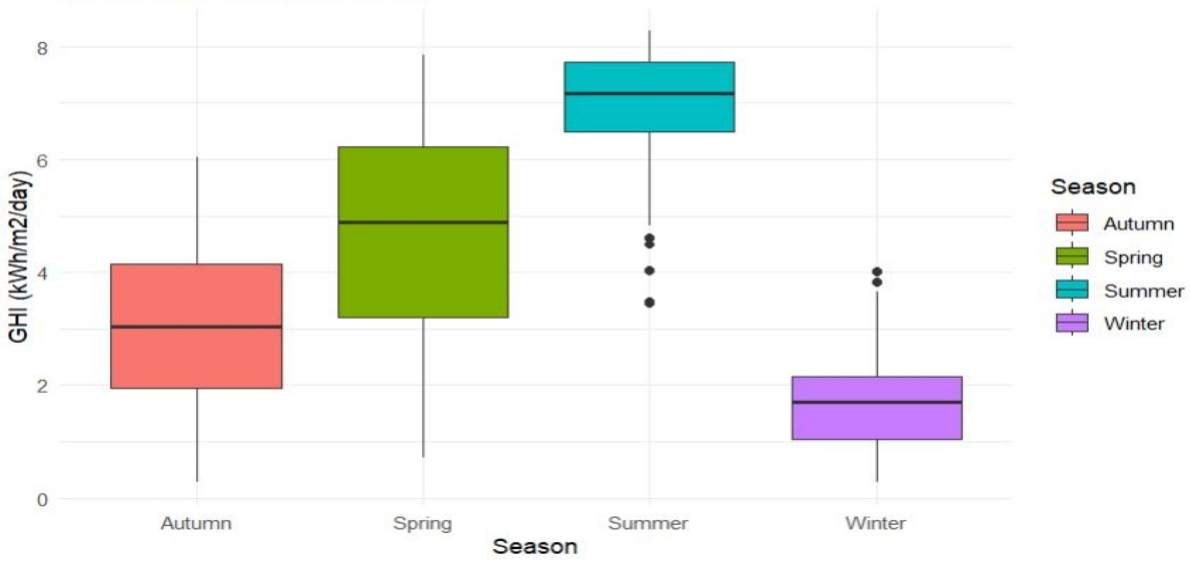


Figure 2. Seasonal Distribution of GHI

Figure 2 illustrates the seasonal distribution of daily GHI values. The boxplot indicates that the highest GHI values are concentrated in summer, while the lowest values are observed in winter. The narrower distribution in summer suggests that solar irradiance is not only higher but also more consistent during this period. In contrast, the broader distribution in winter and transitional seasons reflects greater atmospheric variability. These findings indicate that the RAMS Park location offers more favourable irradiance conditions for preliminary rooftop PV planning during summer months.

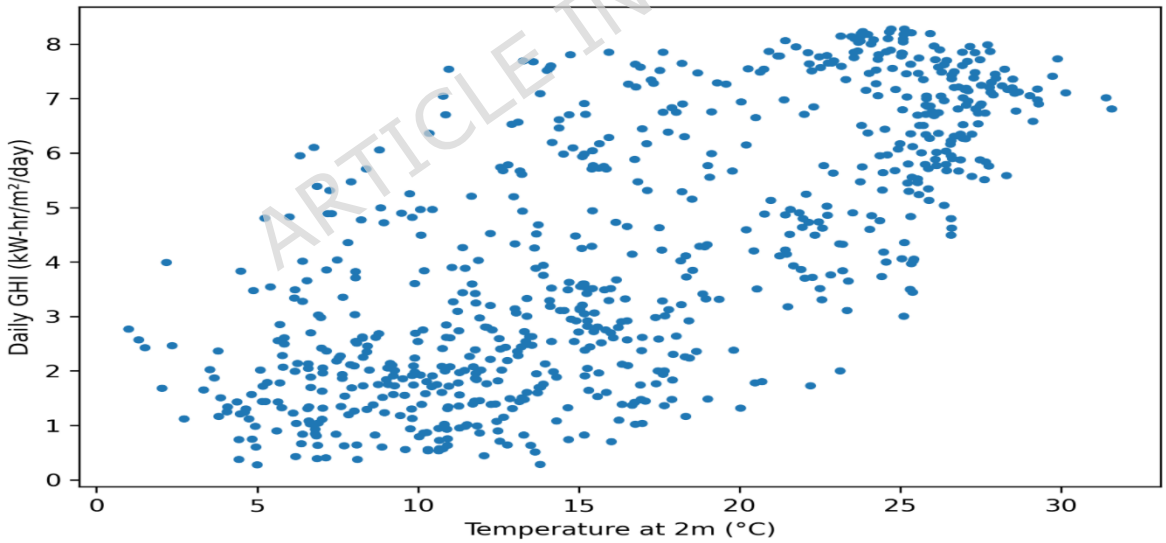


Figure 3. Relationship between GHI and 2-m air temperature

Figure 3 shows the relationship between daily GHI and 2-m air temperature. The scatter pattern suggests that higher GHI values generally coincide with higher air temperatures, particularly during warmer months. However, the relationship should not be interpreted as strictly linear because solar irradiance is also influenced by cloud cover, atmospheric humidity, aerosols, and seasonal solar geometry. Therefore, air temperature is considered here as a contextual meteorological variable rather than a direct predictor of PV output.

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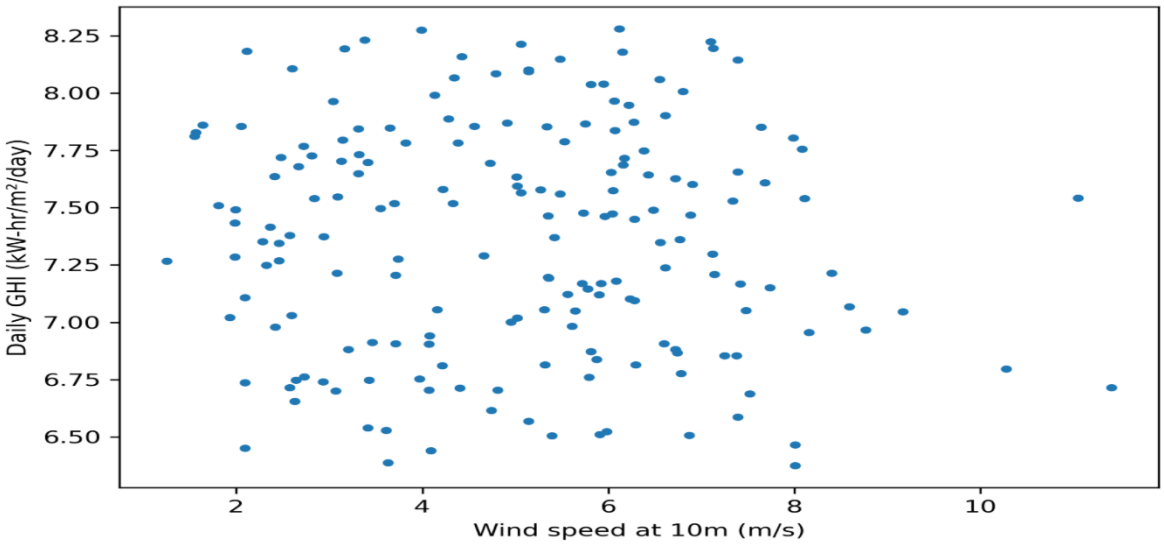


Figure 4. Wind speed distribution on high-GHI days

Figure 4 presents the distribution of 10-m wind speed on days classified as high-GHI days. High-GHI days were defined using the upper quartile of the observed GHI distribution. The figure suggests that high irradiance conditions generally occur under low to moderate wind speeds. However, this result should be interpreted descriptively, as wind speed alone does not determine solar irradiance or PV performance. Instead, the figure provides contextual information on the meteorological conditions accompanying high solar resource availability at the RAMS Park location.

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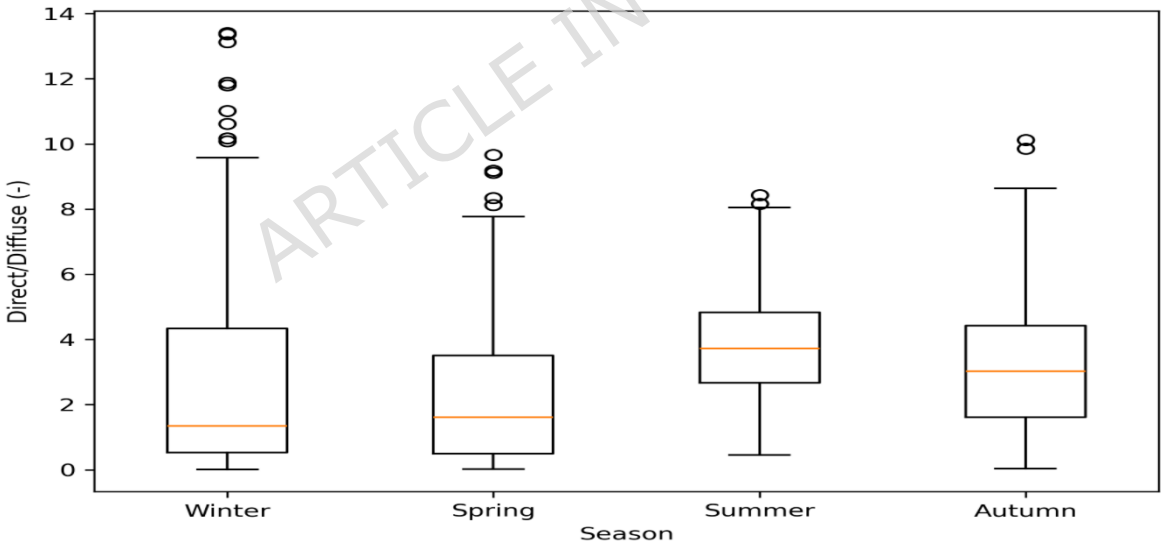


Figure 5. Direct-to-diffuse irradiance ratio

Figure 5 illustrates the relationship between direct and diffuse irradiance components. Higher direct irradiance values generally indicate clearer atmospheric conditions, whereas a relatively higher diffuse component may reflect the influence of cloud cover and atmospheric scattering. The seasonal variation in the direct-to-diffuse relationship provides additional context for interpreting the GHI pattern observed at the RAMS Park location. However, this indicator should be considered as a solar resource characteristic and not as a direct measure of PV system efficiency.

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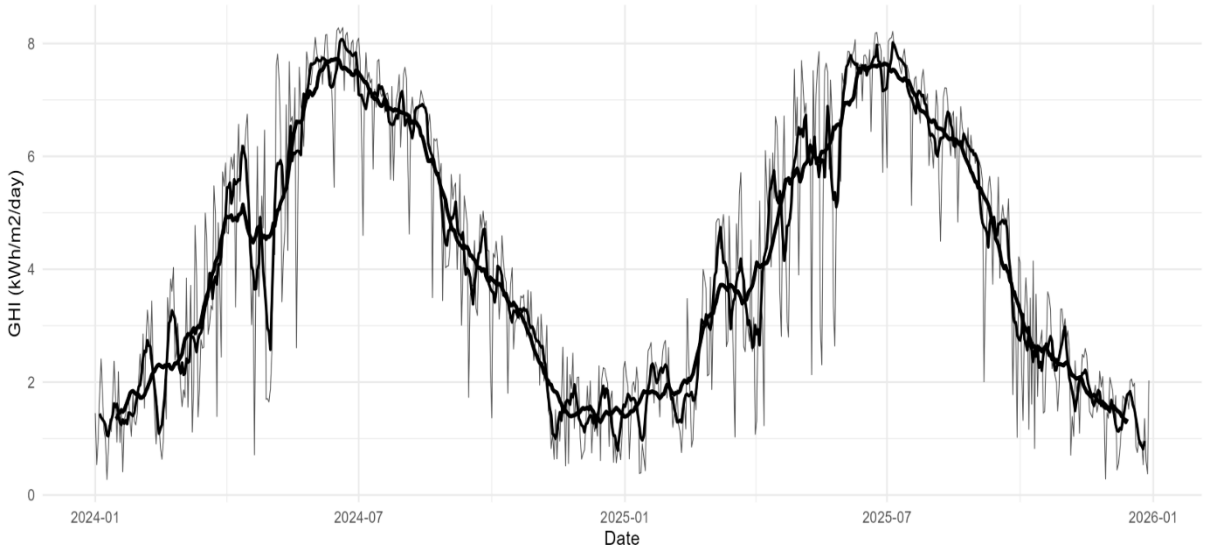


Figure 6. Seven-day and 30-day moving averages of daily GHI

Figure 6 shows the 7-day and 30-day moving averages of daily GHI values. The 7-day moving average captures short-term fluctuations in solar irradiance, whereas the 30-day moving average smooths daily variability and highlights broader seasonal patterns. The moving average results confirm that the dominant temporal structure of the GHI series is seasonal. Therefore, this analysis supports the interpretation that rooftop PV planning at the RAMS Park location should account for strong seasonal differences in solar resource availability.

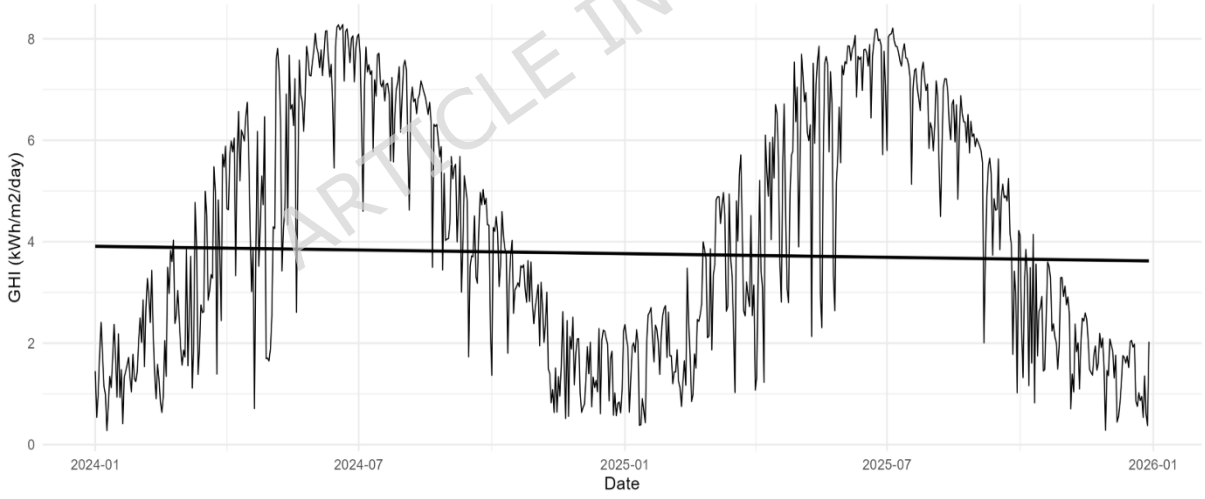


Figure 7. Mann–Kendall trend test and Sen's slope for daily GHI

Figure 7 presents the Mann–Kendall trend test and Sen's slope estimation for daily GHI values. The results indicate that no statistically significant monotonic trend was detected during the analysed 2024–2025 period. Because the dataset covers only two years, this result should be interpreted as short-period temporal behaviour rather than evidence of long-term climatic stability. The near-zero Sen's slope suggests that GHI values did not show a meaningful directional change within the analysed period.

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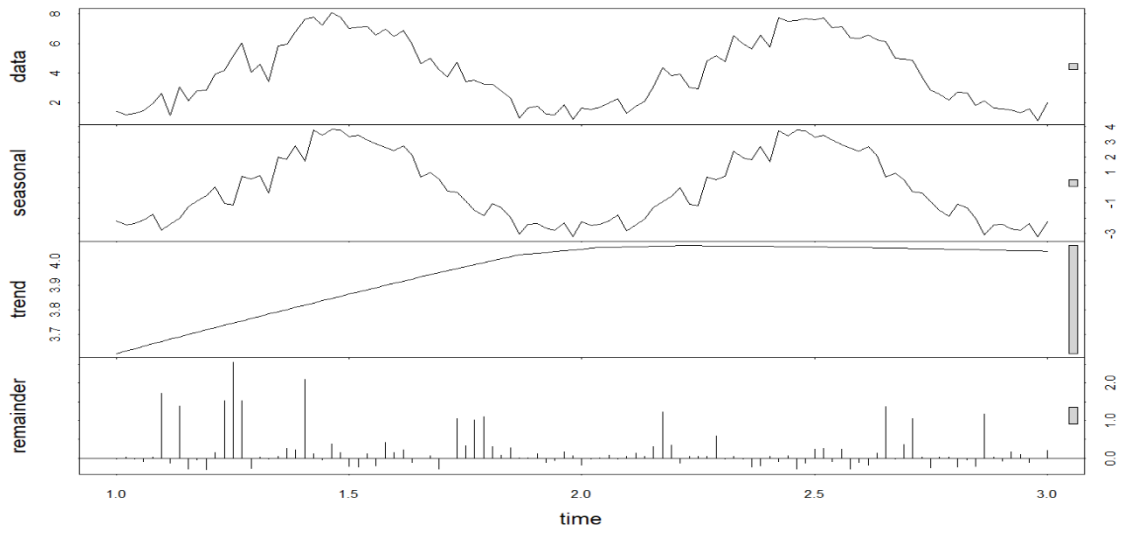


Figure 8. STL decomposition of the GHI time series

Figure 8 presents the STL decomposition of the daily GHI time series into seasonal, trend, and remainder components. The decomposition indicates that the seasonal component is dominant, reflecting the strong annual cycle of solar irradiance. The trend component appears weak over the analysed period, while the remainder component captures short-term irregular fluctuations. These results support the interpretation that seasonal variability is the primary characteristic of solar resource availability at the RAMS Park location.

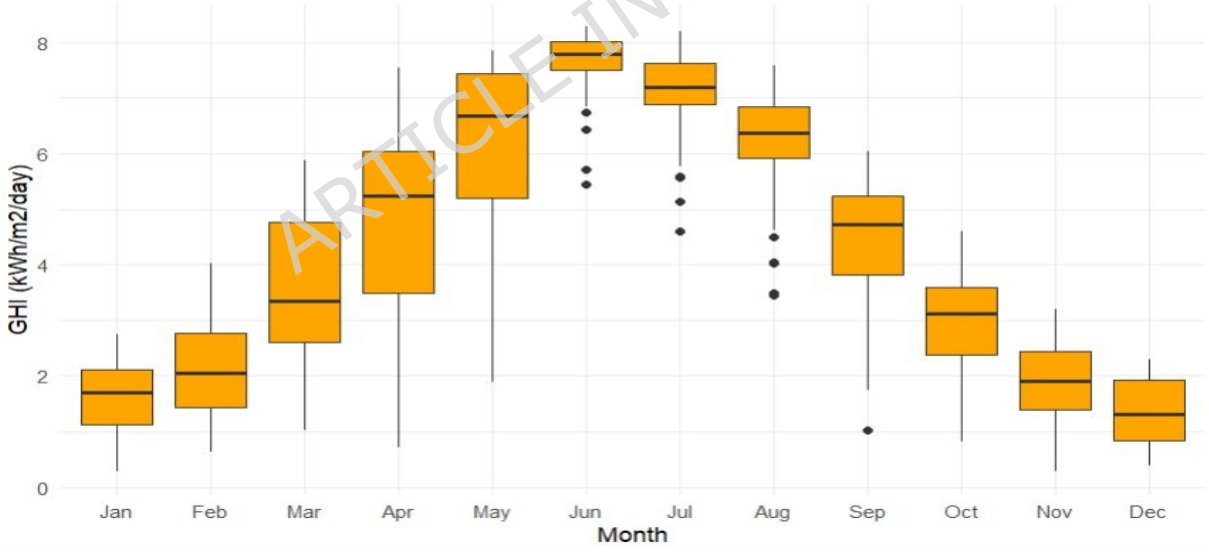


Figure 9. Monthly Variability of Solar Irradiance

Figure 9 shows the monthly variability of daily GHI values. The monthly pattern confirms that solar irradiance is highest during summer and lowest during winter. Greater variability in transitional months indicates that spring and autumn may include both favourable and unfavourable irradiance conditions. This pattern is important for preliminary rooftop PV planning because it highlights the need to consider monthly and seasonal differences rather than relying only on annual average GHI values.

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Table 2 . Descriptive statistics, threshold values and continuity indicators for the daily GHI at RAMS Park (2024–2025).

Variable	Value	Unit
Site	RAMS Park	-
Date start	1.01.2024	-
Date end	29.12.2025	-
n days (calendar)	729	days
n days (valid)	729	days
Missing rate	0	-
GHI mean	4.1458	kWh/m²/day
GHI SD	2.3872	kWh/m²/day
GHI CV	0.5758	-
GHI IQR	4.3853	kWh/m²/day
p01	0.4642	kWh/m²/day
p05	0.8405	kWh/m²/day
p10	1.2117	kWh/m²/day
p25	1.9884	kWh/m²/day
p50 (median)	3.7658	kWh/m²/day
p75	6.3737	kWh/m²/day
p90	7.5437	kWh/m²/day
p95	7.8414	kWh/m²/day
p99	8.1822	kWh/m²/day
Low threshold	1	kWh/m²/day
High threshold (Q3)	6.3737	kWh/m²/day
Availability rate (GHI ≥ low)	0.9287	-
Low-day rate (GHI < low)	0.0713	-
High-day rate (GHI ≥ high)	0.251	-
Mean absolute day-to-day change	0.7904	kWh/m²/day
p95 absolute day-to-day change	2.4846	kWh/m²/day
Low event count	31	-
Low max run length	5	days
Low p90 run length	3	days
High event count	37	-
High max run length	28	days
High p90 run length	14	days

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Table 2 presents the descriptive statistics, threshold values, and irradiance continuity indicators of daily Global Horizontal Irradiance (GHI) at the RAMS Park location for the 2024–2025 period. The dataset consisted of 729 valid daily observations with no missing values, providing a complete two-year daily time series for the analysed period.

The mean daily GHI was 4.1458 kWh/m²/day, with a standard deviation of 2.3872 kWh/m²/day. The coefficient of variation (CV = 0.5758) indicates noticeable variability in daily solar irradiance, which is expected in mid-latitude locations where seasonal cycles and atmospheric conditions strongly affect solar resource availability. The interquartile range (IQR = 4.3853 kWh/m²/day) also indicates a wide difference between lower and upper irradiance conditions.

The percentile distribution shows that very low irradiance values occurred in the lower part of the distribution, with p01 = 0.4642 and p05 = 0.8405 kWh/m²/day, while high irradiance conditions were represented by p90 = 7.5437, p95 = 7.8414, and p99 = 8.1822 kWh/m²/day. The median value of 3.7658 kWh/m²/day indicates that the distribution reflects both low winter values and high summer values.

Low-irradiance days, defined descriptively as days with GHI below 1 kWh/m²/day, accounted for 7.13% of the observations. This threshold should be interpreted as an indicator of very low solar resource availability, not as a technical production threshold for a specific PV system. High-irradiance days, defined using the upper quartile of the observed distribution, represented 25.10% of the dataset. These results suggest that the RAMS Park location includes a substantial proportion of days with favourable solar resource conditions, particularly during high-irradiance periods.

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The mean absolute day-to-day change was 0.7904 kWh/m²/day, while the 95th percentile of day-to-day change reached 2.4846 kWh/m²/day. This indicates that, although average daily variability was moderate, occasional sharp changes in irradiance occurred. Run-length analysis showed that low-irradiance events were relatively short, with a maximum duration of 5 consecutive days, whereas high-irradiance events persisted for up to 28 consecutive days. These continuity indicators are useful for describing solar resource variability and seasonal availability; however, they should not be interpreted as direct evidence of PV system reliability or actual electricity generation performance.

Table 3. Seasonal distribution of daily GHI and irradiance variability indicators.

Season	n_calendar	n_valid	missing_rate	mean_GHI	sd_GHI	cv_GHI	iqr_GHI	low_rate	high_rate
Winter	179	179	0	1.6895	0.8120	0.4806	1.1096	0.2346	0.0000
Spring	184	184	0	4.7458	1.8986	0.4001	3.0312	0.0054	0.2337
Summer	184	184	0	6.9943	0.9559	0.1367	1.2325	0.0000	0.7609
Autumn	182	182	0	3.0751	1.4035	0.4564	2.1865	0.0495	0.0000

Note: Seasons: The months of the year are categorised as follows: Winter (12–2), Spring (3–5), Summer (6–8), Autumn (9–11).

Table 3 presents the seasonal distribution of daily GHI values and related irradiance variability indicators. The results show a clear seasonal pattern. Summer had the highest mean GHI value, with an average of 6.9943 kWh/m²/day, while winter had the lowest mean value, with 1.6895 kWh/m²/day. This difference reflects the strong annual cycle of solar irradiance and indicates that solar resource availability at the RAMS Park location is highly seasonal.

The coefficient of variation was lowest in summer (CV = 0.1367), suggesting that solar irradiance was not only higher but also more consistent during this season. In contrast, winter showed a higher relative variability (CV = 0.4806) and the highest low-irradiance day rate (23.46%). Spring showed relatively favourable average irradiance conditions, with a mean GHI of 4.7458 kWh/m²/day and a high-day rate of 23.37%. Autumn had a lower mean GHI value of 3.0751 kWh/m²/day and no high-irradiance days according to the upper-quartile threshold.

Overall, the seasonal results indicate that summer provides the most favourable period for preliminary rooftop PV planning at RAMS Park, while winter represents the most constrained period in terms of solar resource availability. These findings should be interpreted as seasonal irradiance characteristics rather than direct evidence of PV system output or operational reliability.

Table 4. Mann–Kendall trend test and Sen's slope results for daily GHI.

MK_statistic	p_MK	n	Sen_slope	CI_low	CI_high	p_Sen
-0.996	p = .319	729	-0.000395	-0.001191	0.000374	p = .319

Table 4 presents the Mann–Kendall trend test and Sen's slope estimation results for daily GHI values during the 2024–2025 period. The Mann–Kendall test statistic was −0.996, and the p-value was .319, indicating that no statistically significant monotonic trend was detected in the GHI series during the analysed period. Sen's slope was also very close to zero, suggesting that daily GHI values did not show a meaningful directional increase or decrease within the two-year dataset.

However, these results should be interpreted cautiously. Because the dataset covers only two years, the findings cannot be used to infer long-term climatic stability or long-term solar resource trends. Instead, the results indicate that GHI

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values did not exhibit a statistically significant directional change within the analysed short period. Longer time series and, where possible, ground-based measurements would be required for a more robust long-term solar resource trend assessment.

4. Discussion

The present study examined the temporal and seasonal variability of solar irradiance at RAMS Park Stadium using daily NASA POWER data for the 2024–2025 period. The findings indicate that the solar resource profile at the stadium location is strongly seasonal, with higher and more consistent GHI values during summer and lower, more variable values during winter and transitional periods. This pattern is consistent with previous solar irradiance studies showing that seasonal cycles, cloud cover, atmospheric humidity, aerosol loading, and solar elevation angle play important roles in shaping GHI variability (Liu et al., 2022; Araújo et al., 2024).

Recent studies also emphasise that GHI is a central variable for solar resource assessment because it directly affects the amount of solar energy available for PV conversion. However, GHI is inherently variable due to cloud dynamics, atmospheric scattering, seasonal solar geometry, and local meteorological conditions. Xing et al. (2021) highlighted the importance of accurate GHI estimation for solar energy applications, while Niccolai et al. (2022) emphasised that short-term irradiance variability directly influences PV power production. Therefore, the seasonal and short-term variability observed at RAMS Park should be considered an important preliminary planning factor for future rooftop PV studies rather than a direct measure of PV output.

The descriptive statistics showed a mean daily GHI of approximately 4.15 kWh/m²/day. Although this value suggests a favourable solar resource profile for preliminary rooftop PV planning, it should not be interpreted as direct evidence of PV electricity production. The distinction between irradiance-based resource assessment and complete rooftop PV potential assessment is supported by recent rooftop PV literature. Fakhraian et al. (2021) described rooftop PV potential assessment as a multi-stage process that includes geographical, technical, economic, and practical constraints. Similarly, Bernasconi and Guariso (2021) noted that rooftop PV potential depends not only on solar irradiation but also on available surface area, building characteristics, technology assumptions, and local constraints. In this respect, the present study contributes only to the solar-resource component of rooftop PV planning and should be followed by roof-area estimation, shading analysis, and PV production simulation.

Seasonal analysis demonstrated that summer had the highest average GHI and the lowest coefficient of variation, indicating that solar irradiance was both higher and more consistent during this period. In contrast, winter had the lowest average GHI and the highest proportion of low-irradiance days. These results are important for rooftop PV pre-planning because they show that annual average values alone may not adequately represent monthly and seasonal variations in solar resource availability. For stadiums and other large-scale sports facilities with event-based electricity demand, seasonal resource variability should be considered in future feasibility studies and system simulations.

The moving average and STL decomposition results further confirmed that the dominant structure of the GHI series was seasonal. The 7-day moving average captured short-term atmospheric fluctuations, while the 30-day moving average highlighted broader seasonal patterns. STL decomposition separated the series into seasonal, trend, and remainder components and showed that the seasonal component was dominant. This supports the interpretation that the RAMS Park location has a clear seasonal irradiance pattern, which may be useful for future rooftop PV feasibility and design studies. Time-series decomposition and moving-average approaches are widely used to reveal underlying patterns in solar irradiance series and to distinguish seasonal behaviour from short-term variability (Cleveland et al., 1990; Box et al., 2015).

The Mann–Kendall test and Sen's slope estimation did not detect a statistically significant monotonic trend in daily GHI during the 2024–2025 period. However, because the dataset covers only two years, this result should not be interpreted as evidence of long-term climatic stability. Instead, it indicates that no statistically significant directional change was observed within the analysed short period. Longer time series and, where possible, ground-based measurements would be required to evaluate long-term solar resource trends more robustly. This interpretation is consistent with the methodological caution required in trend analysis of short environmental time series, where

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seasonal structure and limited temporal coverage may restrict the strength of long-term conclusions (Mann, 1945; Kendall, 1975; Sen, 1968; Alashan, 2020).

The use of satellite-based and reanalysis irradiance datasets is common in solar resource assessment, especially when ground-based measurements are unavailable. Nevertheless, recent validation studies suggest that such datasets should be interpreted with caution. Araújo et al. (2024) compared reanalysis-based GHI datasets with ground-based measurements and emphasised the importance of validation in solar resource assessment. Esposito et al. (2024) similarly showed that satellite-derived irradiance products may require benchmarking against ground-based observations, particularly when daily or hourly resolutions are used. Accordingly, the NASA POWER data used in the present study should be viewed as a suitable secondary data source for preliminary assessment, but not as a substitute for site-specific pyranometer measurements.

The direct and diffuse components of irradiance are also relevant for rooftop PV planning because they influence how shading and atmospheric conditions may affect potential PV output. In this study, the direct-to-diffuse irradiance relationship was used only as a descriptive solar-resource characteristic. Tsafarakis and van Sark (2023) emphasised that rooftop PV monitoring and shadow detection are affected by the relationship between direct, diffuse, and global irradiance components. Therefore, future studies should integrate direct and diffuse irradiance information with roof geometry and shading models to estimate its practical effect on PV production.

The low- and high-irradiance event indicators provided additional information on the continuity of solar resource availability. Low-irradiance events were relatively limited and short-lived, while high-irradiance events were more persistent, especially during favourable seasonal periods. Nevertheless, these indicators describe irradiance continuity only. They should not be interpreted as operational reliability metrics of an installed PV system because no monitored electricity production, failure records, maintenance data, or component-level reliability information were included in the analysis. This distinction is particularly important because rooftop and building-integrated PV applications may experience output fluctuations resulting from irradiance intermittency, building characteristics, system configuration, and local environmental constraints (Saurabh & Kumar, 2024).

Overall, the findings suggest that RAMS Park Stadium has a favourable seasonal irradiance profile for preliminary rooftop PV planning, particularly during summer months. However, the results should be interpreted within the limited scope of the study. The analysis provides evidence on solar resource variability and seasonal availability, not on actual PV system performance, risk, or operational reliability. Future research should combine irradiance analysis with roof-area estimation, shading modelling, PV system simulation, electricity demand profiles, economic feasibility analysis, and, where possible, monitored PV production data.

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5. Conclusion

This study provided an irradiance-based preliminary assessment of rooftop PV potential at RAMS Park Stadium using daily NASA POWER data for the 2024–2025 period. Based on the findings, the following conclusions can be drawn:

- RAMS Park Stadium exhibits a clear seasonal irradiance pattern, with daily GHI highest and most consistent in summer and lower and more variable in winter and transitional periods.
- The mean daily GHI of approximately 4.15 kWh/m²/day indicates a favourable solar resource profile for preliminary rooftop PV planning; however, this reflects resource availability only and does not constitute direct evidence of actual PV electricity generation.
- Neither the Mann–Kendall test nor Sen's slope estimation detected a statistically significant monotonic trend in GHI over 2024–2025; given the two-year span, this should be read as short-period temporal behaviour rather than long-term climatic stability.
- Low-irradiance days were limited in proportion and duration, while high-irradiance periods showed greater continuity in favourable seasons; these continuity indicators describe irradiance behaviour only and do not represent the operational reliability of an installed PV system.

In conclusion, RAMS Park Stadium has a favourable seasonal irradiance profile for preliminary rooftop PV planning, particularly during summer months. Nevertheless, the study is limited to an irradiance-based resource assessment and

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does not include PV system design, monitored electricity production, inverter losses, degradation, shading, maintenance records, failure rates, or formal reliability engineering indicators. Future studies should integrate long-term irradiance datasets, roof-area and shading analyses, PV production simulations, electricity demand profiles, and economic feasibility assessments to provide a more comprehensive evaluation of rooftop PV applicability in large-scale sports facilities.

Scope and Limitations of the Assessment

This study should be interpreted as an irradiance-based preliminary assessment of rooftop PV potential rather than a complete PV system performance, risk, or operational reliability analysis. The analysis is based on daily solar irradiance and basic meteorological variables obtained from the NASA POWER database. Therefore, the calculated indicators describe solar resource variability, seasonal availability, short-term fluctuations, and the continuity of low- and high-irradiance periods.

The study does not include installed PV capacity, usable roof area estimation, roof tilt and orientation, module efficiency, inverter losses, shading analysis, soiling, degradation, monitored electricity generation, maintenance records, failure rates, or formal reliability engineering metrics. Previous rooftop PV studies have emphasized that complete PV potential and performance assessments require the combined evaluation of solar resource conditions, roof geometry, technical system parameters, performance losses, and economic feasibility (Bernasconi & Guariso, 2021; Fakhraian et al., 2021). Therefore, the results of the present study should not be interpreted as direct evidence of PV system reliability or actual electricity generation performance.

In addition, the dataset covers only the 2024–2025 period. For this reason, the Mann–Kendall and Sen's slope results were interpreted as short-period temporal behaviour rather than long-term climatic trends. Moreover, NASA POWER data are satellite-based/reanalysis-derived secondary data, and their values may differ from ground-based measurements depending on location, atmospheric conditions, spatial resolution, and temporal aggregation. Recent studies comparing reanalysis or satellite-based irradiance datasets with ground measurements have emphasized the importance of considering data uncertainty and validation when such datasets are used in solar resource assessments (Araújo et al., 2024; Esposito et al., 2024). Accordingly, the findings should be regarded as preliminary evidence for future detailed feasibility studies, PV system simulations, and site-specific engineering assessments.

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Declarations

Ethics Approval

Ethical approval was not required for this study because it used open-access secondary data and did not involve human participants, animal subjects, or personal data.

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Availability of Data and Materials

The raw meteorological and solar irradiance data used in this study are publicly available from the NASA POWER Data Access Viewer. The dataset includes daily Global Horizontal Irradiance (GHI), Direct Irradiance (DIR), Diffuse Irradiance (DHI), 2-m air temperature, and 10-m wind speed data for the RAMS Park Stadium location during the 2024–2025 period.

The processed dataset, variable definitions, and R scripts used to reproduce the analyses, tables, and figures have been uploaded to the Zenodo open-access data repository. The repository includes the cleaned dataset, analysis scripts, figure-generation codes, and a README file describing the data processing workflow. The dataset can be accessed via the following DOI link: 10.5281/zenodo.20665601.

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Competing Interests

The authors declare that they have no known financial interests, personal relationships, institutional affiliations, or competing interests that could have appeared to influence the work reported in this article.

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