

RESEARCH ARTICLE

Optimal Tilt Angle Assessment for Solar Photovoltaic Panels: A Case Study of Coimbatore, India

A. Anto Rashwin^{1*}, J. Ramachandran², S. K. Rajkishore³ and R. Gangai Selvi⁴

¹Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

²Department of Soil and Water Conservation Engineering, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

³Department of Renewable Energy Engineering, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

⁴Department of Physical Sciences and Information Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

ABSTRACT

Optimizing the tilt angle of solar photovoltaic (PV) panels is a key determinant of energy yield, particularly in tropical low-latitude regions where solar geometry and atmospheric conditions differ significantly from those of temperate climates. Coimbatore, Tamil Nadu (11.01°N), possesses high solar energy potential but experiences substantial seasonal variability in cloud cover associated with the southwest and northeast monsoons, influencing the direct and diffuse components of solar radiation. This study evaluates the optimal seasonal and annual tilt angles for solar collectors in Coimbatore using two established solar radiation models: the Liu and Jordan isotropic diffuse radiation model and the Muneer anisotropic radiation model. Seasonal and annual solar radiation incident on tilted surfaces was estimated for tilt angles ranging from 0° to 45° using localized meteorological data. Results from both models indicate that a horizontal (0°) orientation maximizes total incident solar radiation throughout the year, including summer, southwest monsoon, northeast monsoon, and winter seasons. While the Muneer model incorporates anisotropic diffuse radiation and provides a more realistic representation of sky conditions, its predictions closely align with those of the Liu and Jordan model in identifying 0° as the optimum tilt angle. Comparative analysis further reveals that latitude-based tilt recommendations (≈11°) and steeper inclinations (30°–45°) result in lower solar radiation capture, particularly during monsoon periods when diffuse radiation predominates. The findings suggest that in regions located within approximately 10°–15° of the equator, enhanced diffuse radiation interception and reduced cosine losses favour horizontal or near-horizontal PV installations over conventionally tilted systems. These results provide valuable guidance for the design and deployment of photovoltaic and agrovoltaic systems in southern India, supporting improved energy generation, simplified structural requirements, and enhanced economic feasibility.

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*Corresponding author mail: antorashwin@gmail.com



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INTRODUCTION

The global transition toward sustainable and low-carbon energy systems has placed solar photovoltaics (PV) at the forefront of renewable energy deployment due to its scalability, declining costs, and environmental benefits (International Energy Agency [IEA], 2023; REN21, 2022). Among renewable sources, solar energy is uniquely abundant in tropical and subtropical regions, where high annual insolation offers substantial opportunities for large-scale power generation (Duffie & Beckman, 2013). India, in particular, is endowed with favorable solar resources, receiving an average of 4–7 kWh m⁻² day⁻¹ of global solar radiation and approximately 300 clear sunny days per year, making solar PV a central component of its national energy policy (Ministry of New and Renewable Energy [MNRE], 2022; Mani, 2008).

Despite this vast potential, the actual energy yield of many PV installations in India remains below theoretical expectations, primarily due to non-optimized system design parameters such as panel orientation, tilt angle, and reliance on static installation practices (Sukhatme & Nayak, 2017; Sharma *et al.*, 2020). The efficiency of a solar panel is governed by the angle of incidence, defined as the angle between incoming solar radiation and the normal to the panel surface. As this angle increases, cosine losses become significant, leading to reduced energy capture even under high irradiance conditions (Duffie & Beckman, 2013).

A widely adopted rule of thumb recommends setting the panel tilt angle equal to the local latitude to maximize annual energy yield. While this approximation is convenient, it fails to adequately account for seasonal variations in solar declination and the complex atmospheric conditions characteristic of tropical climates (El-Sebaï *et al.*, 2010; Yadav & Chandel, 2013). In low-latitude regions, where the sun remains close to the zenith for much of the year, latitude-based tilt angles increase cosine losses during peak radiation hours, thereby reducing overall system performance (Khatib *et al.*, 2012).

The treatment of diffuse sky radiation is central to accurately estimating solar radiation incident on tilted surfaces, which is essential for reliable PV performance assessment and optimization. Since most meteorological stations measure solar radiation on horizontal surfaces, transposition models are used to convert global horizontal irradiance (GHI) to

the radiation received by inclined collectors (Iqbal, 1983). Traditional isotropic models, such as the Liu and Jordan model, assume uniform diffuse radiation across the sky dome (Liu & Jordan, 1961). While simple and computationally efficient, this assumption does not reflect real atmospheric behavior, particularly under cloudy and humid conditions where diffuse radiation dominates.

In reality, sky radiance is anisotropic, exhibiting higher intensity near the solar disc (circumsolar region) and along the horizon due to multiple scattering processes and atmospheric composition (Perez *et al.*, 1990; Reindl *et al.*, 1990). This anisotropy becomes especially pronounced in tropical monsoon regions, where cloud cover, aerosols, and water vapor significantly alter the balance between direct and diffuse radiation (Muneer, 1997; Kasten, 1996). Consequently, advanced anisotropic models are increasingly recommended for accurate estimation of solar radiation in such environments.

Coimbatore, Tamil Nadu, located at approximately 11.02° N latitude, represents a tropical inland location with high solar potential and pronounced seasonal variability associated with the Southwest and Northeast monsoons. The region receives a mean GHI of 5.0–5.5 kWh m⁻² day⁻¹, but the proportion of diffuse radiation increases substantially during the monsoon months (Mani & Rangarajan, 1982; NASA POWER, 2024). These climatic characteristics necessitate the use of radiation models that accurately capture anisotropic sky conditions.

In this context, the present study employs two complementary radiation models: the Liu and Jordan isotropic model and the Muneer radiation model. The Muneer model is an advanced physical–empirical anisotropic formulation that distinguishes between sunlit and shaded sky components and performs reliably under both clear and overcast conditions (Muneer, 1997; Muneer & Gul, 2000). It is particularly robust for tropical and subtropical regions, where diffuse radiation contributes significantly to total irradiance on tilted surfaces. The primary objective of this research is to estimate optimal seasonal tilt angles for solar collectors in Coimbatore to minimize cosine losses and maximize total incident radiation. Specifically, the study aims to: (i) analyze monthly and seasonal solar radiation patterns characteristic of the Coimbatore climate;

(ii) evaluate the performance of solar panels under fixed latitude-based tilt and seasonally optimized configurations; and (iii) compare isotropic and anisotropic radiation modeling approaches to assess their implications for low-latitude PV system design. The findings are expected to provide evidence-based guidance to improve solar PV performance in tropical monsoon-dominated regions and support decision-making for solar developers and policymakers in Southern India.

METHODOLOGY

The methodology adopted in this study follows a structured computational framework to identify the most effective seasonal tilt angles for solar panels in Coimbatore. It integrates high-resolution, long-term solar radiation data with mathematical modelling of solar irradiance components and an iterative simulation process to optimize tilt angle.

Study Location and Environmental Profile

The study focuses on Coimbatore, Tamil Nadu, located at 11.0121°N, 76.9558°E. Owing to its tropical location near the equator, the region exhibits high solar potential year-round; however, pronounced variations in cloud cover during the Southwest and Northeast monsoon seasons significantly influence the availability and distribution of solar radiation.

Data Acquisition (NASA POWER)

To ensure statistical robustness and reliability, daily solar radiation data were obtained from the NASA POWER database. A 20-year temporal window from 2004 to 2024 was selected to capture long-term climatic variability and decadal-scale solar fluctuations. The dataset comprises Daily Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI), which together form the basis for detailed irradiance decomposition and tilt optimization. The use of this extended long-term dataset provides a more reliable baseline than short-term meteorological records, effectively smoothing anomalies arising from extreme weather events and interannual variability.

Solar Radiation Models

Solar radiation models play a crucial role in solar energy assessment, system design, and performance optimization. Since most meteorological stations measure solar radiation on a horizontal surface, models are required to estimate radiation on tilted planes, which is essential for photovoltaic (PV)

panels and solar thermal collectors. These models decompose global solar radiation into its beam (direct), diffuse, and reflected components, then transform them from the horizontal to an inclined surface. Their importance lies in improving the accuracy of energy yield estimation, optimizing panel tilt and orientation, and supporting long-term feasibility studies. By incorporating atmospheric conditions, cloudiness, and sky distribution characteristics, solar radiation models help bridge the gap between measured data and real-world system performance.

Liu and Jordan Model

The Liu and Jordan Model is one of the earliest and most widely used solar radiation transposition models. It assumes that diffuse solar radiation is isotropically distributed across the sky dome, meaning it arrives uniformly from all directions. Under this assumption, the diffuse component on a tilted surface depends only on the tilt angle, not on the sun's position. The advantages are a simple mathematical formulation and ease of implementation; it requires minimal input data, making it suitable for regions with limited measurements, and is computationally efficient and widely adopted in preliminary design studies.

$$H_T = H \left[(1 - r_d) \cdot R_b + r_d \cdot \left(\frac{1 + \cos \beta}{2} \right) + \rho \cdot \left(\frac{1 - \cos \beta}{2} \right) \right]$$

Where

H_T = Total solar radiation on the tilted surface (MJ/m²/day)

H = Total global solar radiation on a horizontal surface (MJ/m²/day)

r_d = Diffuse fraction = $H_d \setminus H$ (can be estimated from K_t)

β = Tilt angle of the panel (°)

R_b = Ratio of beam radiation on tilted to horizontal surface

ρ = Ground reflectance or albedo (typically 0.2 for crops)

The Liu and Jordan model is particularly useful for initial solar potential assessments, educational purposes, and locations with relatively clear skies where anisotropic effects are less dominant. Its simplicity makes it a benchmark model against which more advanced approaches are often compared.

MUNEER MODEL

The Muneer Model is an advanced anisotropic solar radiation model that accounts for the non-uniform distribution of diffuse radiation across the sky. Unlike isotropic models, it considers circumsolar brightening and horizon effects, which become significant under cloudy, humid, and monsoon-influenced conditions. The advantages include a more realistic representation of diffuse sky radiation, better performance under partially cloudy and overcast conditions, and the incorporation of atmospheric variability, improving accuracy in tropical and coastal regions.

$$H_T = H_b R_b + H_d \left[C_1 \cdot R_b + (1 - C_1) \cdot \frac{1 + \cos \beta}{2} \right] + \rho H \cdot \frac{1 - \cos \beta}{2}$$

Where

H_T = Global radiation on a tilted surface (MJ/m²/day)

H = Global horizontal radiation (MJ/m²/day)

H_b = Beam (direct) radiation (MJ/m²/day)

H_d = Diffuse radiation (MJ/m²/day)

β = Tilt angle of panel (°)

R_b = Ratio of beam radiation on tilted to horizontal surface

ρ = Ground albedo (typically 0.2 for vegetation)

C_1 = Diffuse anisotropy factor based on clearness index K_t

The Muneer model is especially valuable for detailed system design and seasonal tilt optimization in regions with high diffuse radiation fractions, such as monsoon-dominated climates. Capturing anisotropic sky behavior provides more reliable estimates of incident radiation on tilted surfaces, leading to improved prediction of PV energy output and system efficiency.

RESULTS AND DISCUSSION

Performance of Muneer Radiation Model

The performance of the Muneer Radiation Model, evaluated using 20 years (2004–2024) of NASA POWER meteorological data, provides a detailed and reliable assessment of the solar energy potential of Coimbatore. The long-term simulations reveal a clear seasonal variation in incident solar radiation harvested at optimized tilt angles, reflecting the combined influence of solar geometry, atmospheric conditions, and regional climatic patterns. As illustrated in

Figure 1, the total annual solar radiation is unevenly distributed across the region's four dominant seasons, with a pronounced concentration in the middle of the year.

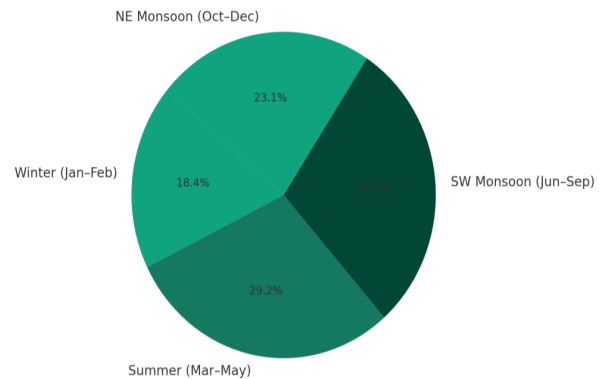


Fig. 1 Distribution of total annual solar radiation

The analysis indicates that the Summer and Southwest Monsoon seasons are the most productive, together accounting for 58.5% (nearly 60%) of the annual solar radiation potential. Notably, the Southwest Monsoon season (29.3%) marginally exceeds the summer season (29.2%) in its contribution, a result attributed to longer day lengths during the June–September period and Coimbatore's location on the leeward side of the Western Ghats, which often experiences relatively higher irradiance levels despite monsoonal cloud cover. In contrast, the Northeast Monsoon (23.1%) and Winter (18.4%) seasons contribute comparatively less to the annual total, primarily due to shorter day lengths and increased cloudiness during the retreating monsoon phase from October to December. These findings emphasize the importance of seasonal tilt optimization, as nearly 60% of the annual energy yield can be maximized by focusing on the Summer and Southwest Monsoon periods alone. The simulations further demonstrate that a conventional fixed-tilt system, typically set equal to the site latitude of 11.0121°N, would incur notable cosine losses during peak radiation periods. In contrast, seasonal adjustments derived from the Muneer Radiation Model substantially enhance the capture efficiency of total incident radiation (IT). A key outcome of the study is that a 0° (horizontal) tilt angle emerges as the most effective configuration for maximizing solar radiation capture across all seasons in Coimbatore. This result is primarily driven by the region's low-latitude

setting and the consistently high proportion of diffuse radiation throughout the year, conditions that the anisotropic Muneer model more accurately represents than by traditional isotropic approaches.

An in-depth seasonal analysis further clarifies the dominance of a horizontal orientation for solar energy harvesting in Coimbatore. The high-yield period, comprising the Summer and Southwest Monsoon seasons, together contributes nearly 60% of the region's annual solar energy potential. During the Summer months (March–May), solar radiation is strongly dominated by the direct beam component, as the sun's apparent path remains almost overhead at a latitude of approximately 11°N . Under such conditions, a 0° tilt minimizes cosine losses, making a horizontal surface the most efficient configuration for direct solar capture. During the Southwest Monsoon season (June–September), despite frequent cloud cover, the total seasonal radiation slightly exceeds that of summer, reaching about 1769.53 MJ m^{-2} . The Muneer Radiation Model explains this outcome by highlighting the dominance of diffuse radiation under cloudy conditions, where a flat panel captures radiation from the entire sky dome. In contrast, a tilted surface effectively obscures part of the diffuse sky, reducing the net radiation intercepted. Fig. 2 summarizes the cumulative radiation and performance characteristics for each season at the optimal 0° tilt. The low-yield

period, comprising the Northeast Monsoon and Winter seasons, further reinforces this behaviour. During the Northeast Monsoon (October–December), scattered rainfall and persistent overcast skies prevail, and a 0° tilt remains optimal, enabling stable energy output through uniform capture of diffuse radiation from all directions of the sky vault. In Winter (January–February), although cumulative radiation is the lowest of the year (approximately 1112.55 MJ m^{-2} , clearer skies improve instantaneous panel performance. Even with a lower solar altitude during these months, the Muneer model predicts that a horizontal orientation continues to yield the highest total daily radiation.

Overall, the model's treatment of an anisotropic sky, acknowledging enhanced brightness near the sun and along the horizon, confirms that for low-latitude regions such as Coimbatore, a 0° tilt is universally optimal throughout the year. This flat orientation maximizes the combined capture of direct beam radiation during clear summer conditions and diffuse radiation during the monsoon and winter seasons. From a practical standpoint, the findings suggest that horizontal or very low-tilt installations are not only structurally simpler but also the most energy-efficient in terms of mathematical analysis for the atmospheric conditions typical of Tamil Nadu, which lies close to the equator and experiences substantial diffuse radiation during much of the year.

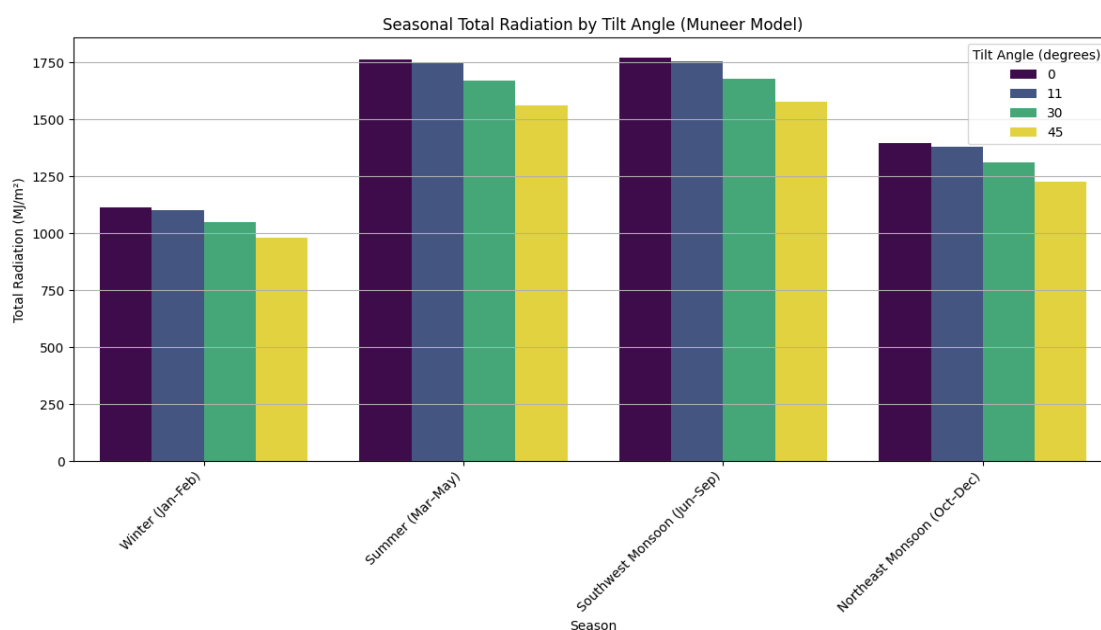


Fig. 2 Seasonal Total Solar Radiation based on Muneer Model for Different Tilt Angles

The comparative analysis of cumulative radiation as a function of tilt angle further substantiates this conclusion. Simulations conducted over a tilt range of 0° to 45° using the Muneer model reveal an inverse relationship between tilt angle and seasonal radiation capture. In all four seasons, the maximum total radiation occurs in a horizontal orientation. As the tilt angle increases from 1° to 45° , a steady and measurable decline in total incident radiation is observed. Notably, even the commonly adopted “latitude-equivalent” tilt of about 11° yields lower energy harvesting than a flat configuration, particularly during the monsoon seasons, when diffuse radiation dominates. This consistent trend underscores that, at low latitudes, the benefits of full sky-dome exposure outweigh the gains from tilting panels toward the direct beam.

Performance of the Liu and Jordan Model

To validate the robustness of the results obtained from the anisotropic Muneer Radiation Model, a comparative analysis was carried out using the Liu and Jordan isotropic model, which is widely regarded as a benchmark approach in solar engineering and assumes uniform diffuse sky radiation across the entire sky dome. The simulation results from the Liu and Jordan model show strong agreement with the Muneer model in identifying the optimal panel orientation for Coimbatore (11.0121°N). Across all four seasons, Summer, Winter, Southwest Monsoon, and Northeast Monsoon, a 0° (horizontal) tilt consistently yielded the highest total solar radiation. This consistency indicates that, even under the simplifying assumption of isotropic sky brightness, the underlying solar geometry at this low latitude inherently favors a horizontal surface to maximize energy capture throughout the year.

The analysis further reveals a systematic degradation in radiation capture as the tilt angle increases from the horizontal plane to commonly adopted installation angles. When the panels were inclined at approximately 11° , which corresponds to the local latitude and is often recommended as standard practice, a measurable reduction in total radiation was observed. The Liu and Jordan model confirms that this conventional latitude-based tilt results in lower efficiency under the tropical climatic conditions in Coimbatore. At steeper inclinations, such as 30° , the decline in total radiation becomes more pronounced, as panels increasingly miss a substantial fraction of diffuse radiation and experience higher

cosine losses when the sun is near zenith, a frequent condition at this latitude.

The convergence of the anisotropic Muneer model and the isotropic Liu and Jordan model at a 0° optimal tilt provides high confidence in the validity of the findings. This agreement can be attributed to three interrelated physical factors. First, Coimbatore’s proximity to the equator ensures that the sun remains at a high altitude for most of the year, often close to the zenith. Under these conditions, a horizontal panel remains more nearly perpendicular to incoming solar rays during peak hours than a tilted surface, thereby minimizing cosine losses. Second, the diffuse component of solar radiation is substantial in this tropical region, particularly during the Southwest and Northeast monsoon seasons, which together extend over nearly seven months of the year. Horizontal panels benefit from an unobstructed 180° view of the sky vault, enabling uniform capture of scattered radiation from all directions, whereas tilted panels effectively shield part of the sky and reduce diffuse energy collection. Third, the results reinforce a broader “low-latitude rule” in solar harvesting, whereby regions located within approximately 10° – 15° of the equator gain little advantage from latitude-based tilting, as geometric and diffuse-radiation losses often outweigh the benefits of aligning with the seasonal solar path.

In summary, the convergence of both radiation models, despite their differing assumptions regarding sky brightness, demonstrates that a horizontal (0°) orientation is the most robust, year-round solution for Coimbatore. While seasonal tilt adjustments are frequently promoted as a means to enhance solar energy yield, the findings clearly show that at this low latitude, a flat panel configuration naturally optimizes energy capture by maximizing direct beam radiation during clear summer months and diffuse radiation during the monsoon seasons.

Percentage reduction in power generation

The percentage reduction in power generation relative to the optimal 0° tilt clearly demonstrates the sensitivity of solar energy capture to panel inclination in the low-latitude climate of Coimbatore. Across all seasons, even a modest increase in tilt to 11° (latitude tilt) results in a measurable but consistent decline in energy yield, ranging from about 0.9% in summer to 1.8% during the Northeast Monsoon. This indicates that while the losses

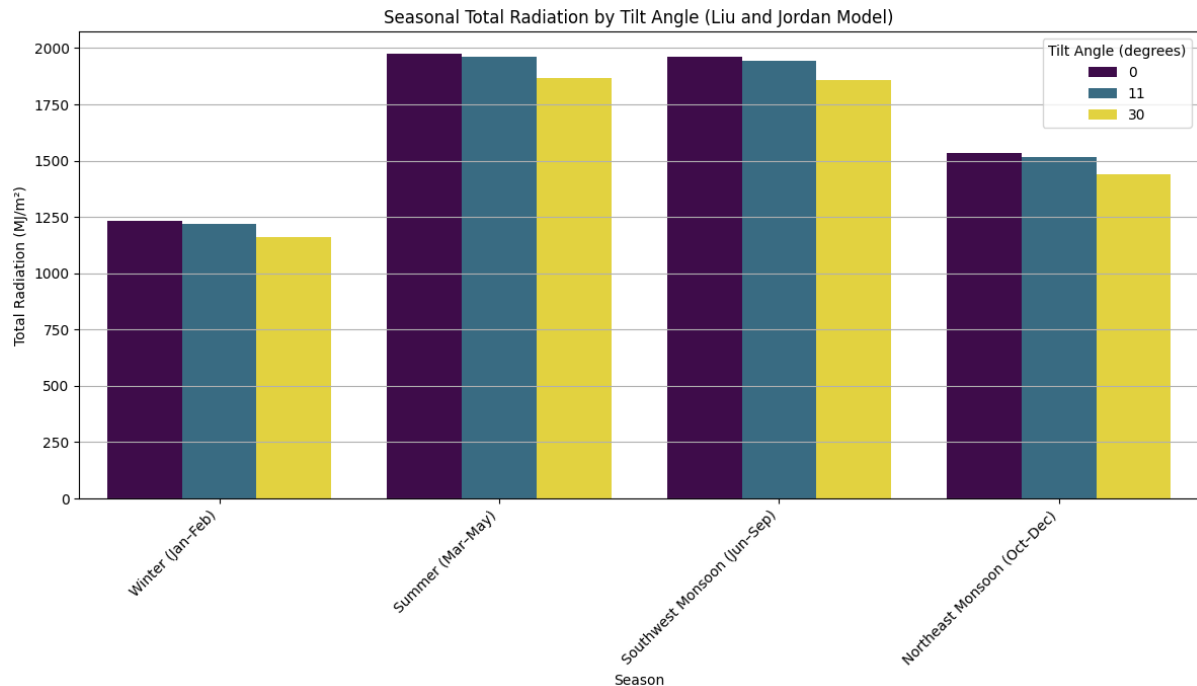


Fig. 3 Seasonal Total Solar Radiation based on the Liu and Jordan Model for Different Tilt Angles

at latitude tilt are relatively small, they are persistent throughout the year and become more pronounced during seasons dominated by diffuse radiation. As the tilt angle increases to 30°, the reduction in power generation becomes substantial, ranging from approximately 4.9% to 6.3%, reflecting increased cosine losses and reduced exposure to the diffuse sky dome. The most severe losses occur at a steep tilt of 45°, where power generation decreases by about 11–13% across all seasons, underscoring the strong disadvantage of steep inclinations in tropical regions. Overall, the inference from this analysis is that any deviation from a horizontal orientation results in progressive, systematic energy losses in Coimbatore, with the impact becoming increasingly significant at higher tilt angles. These results reinforce that a 0° or very low tilt configuration is the most energy-efficient choice for year-round solar power generation at low latitudes, particularly in climates with high diffuse radiation during monsoon periods.

CONCLUSION

The optimization of solar panel tilt angles in Coimbatore (11.0121°N) is a critical determinant of photovoltaic performance in a region with high solar potential and pronounced monsoonal influences. Through the combined application of the anisotropic Muneer radiation model and the isotropic Liu and Jordan model, this study conclusively demonstrates the superiority of a 0° (horizontal) panel orientation for maximizing solar radiation capture across all seasons. Coimbatore's low-latitude setting ensures that the sun remains close to the zenith for much of the year, enabling flat panels to intercept direct beam radiation with minimal cosine losses. Simultaneously, the horizontal configuration proves especially advantageous during the Southwest and Northeast monsoon periods, when diffuse radiation dominates, as it provides an unobstructed view of the entire sky dome and maximizes the capture of scattered light.

Approximate Percentage Reduction in Power Generation Compared to 0° Tilt

Season	11° Tilt	30° Tilt	45° Tilt
Winter (Jan–Feb)	-1.3%	-5.6%	-12.6%
Summer (Mar–May)	-0.9%	-5.5%	-12.1%
SW Monsoon (Jun–Sep)	-1.0%	-4.9%	-11.0%
NE Monsoon (Oct–Dec)	-1.8%	-6.3%	-11.3%

While both models converge on the same optimal tilt, the Muneer model offers greater sensitivity by accounting for the anisotropic distribution of sky brightness, thereby delivering more realistic estimates under tropical and monsoon-influenced conditions. The observed seasonal variations in total radiation further confirm that conventional latitude-based tilt practices, such as inclinations of 11° or steeper angles like 30° , lead to systematic and avoidable reductions in annual energy yield at this latitude. Looking ahead, future research should extend these findings through hourly-resolution simulations, field-level validation using operational PV systems, and integration within agrovoltaic frameworks to assess land-use synergies. Additionally, cross-comparisons with more advanced transposition models could further refine performance predictions for emerging technologies such as bifacial and tracking systems. Overall, the adoption of a horizontal or very low-tilt configuration, grounded in robust model-based evidence, offers a practical and scientifically justified pathway for enhancing the efficiency, reliability, and economic viability of solar photovoltaic installations in Coimbatore and similar low-latitude regions.

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Ethics Statement

This study did not involve human participants, animals, or biological materials requiring ethical approval. Therefore, ethical approval was not required.

Originality and Plagiarism

The authors declare that this manuscript is an original work and has not been published previously in whole or in part. All sources of information have been appropriately cited and acknowledged.

Consent for Publication

All authors have read and approved the final version of the manuscript and consent to its publication in the journal.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this manuscript.

Data Availability

The data supporting the findings of this study are available from publicly accessible sources, including the NASA POWER database. Data generated or analyzed during this study may be obtained from the corresponding author upon reasonable request.

Author Contributions:

A.A.R.: Conceptualization, Methodology, Data Curation, Formal Analysis, Writing – Original Draft.

J.R.: Conceptualization, Methodology, Visualization, Supervision, Writing – Original Draft.

S.K.R.: Validation, Writing – Review & Editing.

R.G.S.: Validation, Writing – Review & Editing.

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