

Investigation of Optimal Tilt Angle for Solar PV Panels in Lhasa

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Abstract: Solar energy is a rapidly growing renewable energy resource in the Tibetan Plateau, where high altitude and clear skies provide exceptional solar irradiance. The tilt angle of photovoltaic (PV) panels significantly affects the amount of solar radiation received and consequently the energy output of PV systems. This study investigates the optimal tilt angle for solar PV panels in Lhasa, Tibet (29.65°N, 91.13°E, 3,656 m elevation) during winter. Solar irradiance measurements were collected at ten different tilt angles ranging from 36° to 45° at hourly intervals from 9:00 to 17:00 over three consecutive clear-sky days in January 2025. Statistical analysis revealed that the 44° tilt angle yielded the highest average irradiance of 815.2 W/m² and the maximum daily total irradiation of 7.07 kWh/m²/day. The performance difference across the 36°–45° range was relatively modest (3.3%), with angles between 41° and 45° all exceeding 800 W/m² average irradiance. Afternoon irradiance was consistently higher than morning irradiance across all tilt angles, with peak values occurring between 13:00 and 14:00. These findings provide practical guidance for the design and installation of solar PV systems in the Lhasa region and contribute to the optimization of solar energy utilization in high-altitude plateau environments.

Keywords: Solar irradiance, tilt angle, photovoltaic panels, Lhasa, Tibet, high altitude, winter performance.

1. Introduction

Solar energy has emerged as one of the most promising renewable energy sources worldwide, and its utilization is particularly advantageous in high-altitude regions with abundant sunshine. The Tibetan Plateau, often referred to as the "Roof of the World," possesses some of the highest solar radiation levels in China, with annual sunshine hours exceeding 3,000 hours in many areas [1]. Lhasa, the capital city of the Tibet Autonomous Region, is renowned for its exceptional solar resources, earning it the nickname "Sunlight City."

The performance of photovoltaic (PV) systems depends on multiple factors, including solar irradiance, ambient temperature, panel efficiency, and installation configuration. Among these factors, the tilt angle of PV panels plays a critical role in determining the amount of incident solar radiation [2]. An optimally tilted panel maximizes the absorption of solar energy throughout the day and across seasons, directly improving energy yield and economic returns on investment.

Numerous studies have investigated optimal tilt angles for different geographic locations. The general rule of thumb suggests that the optimal tilt angle is approximately equal to the latitude of the installation site for maximum annual energy production [3]. However, this approximation may not hold for all locations, particularly in high-altitude regions where atmospheric conditions, albedo effects, and seasonal variations differ significantly from low-altitude areas.

For high-altitude regions like the Tibetan Plateau, several unique factors influence solar irradiance on tilted surfaces:

Thinner atmosphere: At 3,656 m elevation, the reduced atmospheric mass results in higher direct normal irradiance (DNI) compared to sea-level locations [4].

Strong albedo reflection: Snow cover during winter can significantly increase ground-reflected radiation, which may favor steeper tilt angles that capture more reflected light [5].

Cold temperatures: Low ambient temperatures improve PV

panel efficiency, making winter solar energy production particularly valuable in this region.

Clear sky conditions: The Tibetan Plateau experiences a high frequency of clear-sky days, especially during winter, resulting in stable and predictable irradiance patterns.

Despite the importance of optimal tilt angle for PV system design, limited field measurement data exist specifically for the Lhasa region, particularly for winter conditions. Most existing studies rely on modeled data or satellite-derived irradiance values, which may not accurately represent local conditions.

This study aims to fill this gap by presenting field-measured solar irradiance data at multiple tilt angles in Lhasa during winter. The specific objectives are: (1) to quantify the relationship between tilt angle and solar irradiance under winter conditions; (2) to determine the optimal tilt angle for maximum energy capture; (3) to analyze diurnal and day-to-day variations in irradiance across different tilt angles; and (4) to provide practical recommendations for PV system installation in the Lhasa region.

The findings of this study will be valuable for engineers, policymakers, and researchers involved in solar energy development on the Tibetan Plateau. Accurate determination of optimal tilt angles can significantly improve the economic viability and energy output of PV systems in this resource-rich but economically developing region.

2. Materials and Methods

2.1. Study Site

The experiment was conducted on the rooftop of an office building in Lhasa, Tibet Autonomous Region, China (29.65°N, 91.13°E). The site is located at an elevation of approximately 3,656 meters above sea level. Lhasa has a temperate plateau monsoon climate with distinct dry and wet seasons. Winter (December–February) is characterized by cold temperatures, low humidity, and exceptionally clear skies, with monthly average sunshine duration exceeding 240

hours in January [6].

The surrounding environment consists of urban infrastructure with no significant obstructions to the south, ensuring unobstructed solar access throughout the day. The rooftop location provides a representative setting for typical building-integrated PV installations in the region.

2.2. Experimental Setup

Flat-plate solar collectors were used as measurement surfaces to assess solar irradiance at different tilt angles. Ten tilt angles were tested, ranging from 36° to 45° in 1° increments (36°, 37°, 38°, 39°, 40°, 41°, 42°, 43°, 44°, and 45°). This range was selected based on the latitude of Lhasa (approximately 29.65°N) and the expectation that winter optimal angles would be steeper than the latitude angle.

The collectors were mounted on adjustable frames that allowed precise setting of the tilt angle. All collectors faced due south (azimuth angle = 0°), which is the standard orientation for maximum solar energy collection in the Northern Hemisphere. The measurement surfaces were calibrated to ensure consistent and comparable readings across all tilt angles.

2.3. Data Collection

Solar irradiance measurements were collected over three consecutive days during the winter period: January 28, 29, and 30, 2025. All three days were clear-sky days with no significant cloud cover, ensuring consistent and comparable measurement conditions.

Irradiance data were recorded at hourly intervals from 9:00 to 17:00 local time, covering the primary daylight period during winter. For each time point, irradiance values (in W/m²) were measured simultaneously for all ten tilt angles. The measurement protocol ensured that readings were taken under stable solar conditions at each hour, minimizing transient effects from passing clouds or atmospheric disturbances.

2.4. Data Analysis

The collected data were organized and analyzed using statistical methods to determine the optimal tilt angle and characterize irradiance patterns. The following analyses were performed:

(1) Average irradiance by tilt angle: For each tilt angle, the mean and standard deviation of irradiance values across all time points and all three days were calculated.

(2) Daily total irradiation: The daily total solar irradiation (in kWh/m²/day) was computed by summing the hourly irradiance values from 9:00 to 17:00. This metric represents the total energy received per unit area over the measurement period.

(3) Diurnal variation analysis: The temporal pattern of irradiance throughout the day was analyzed for each tilt angle to identify peak irradiance times and morning-afternoon asymmetry.

(4) Morning vs. afternoon comparison: Average morning (9:00–12:00) and afternoon (13:00–17:00) irradiance values were compared across tilt angles to assess the impact of tilt angle on morning versus afternoon energy capture.

(5) Day-to-day variability: The consistency of irradiance patterns across the three measurement days was evaluated to assess the reliability of the findings.

All statistical analyses were performed using Python with NumPy and pandas libraries. Visualization was conducted using matplotlib to generate charts illustrating the key findings.

3. Results and Analysis

3.1. Overall Irradiance Performance by Tilt Angle

The average solar irradiance across all measurement periods (9:00–17:00, three days) for each tilt angle is presented in Figure 1 and Table 1.

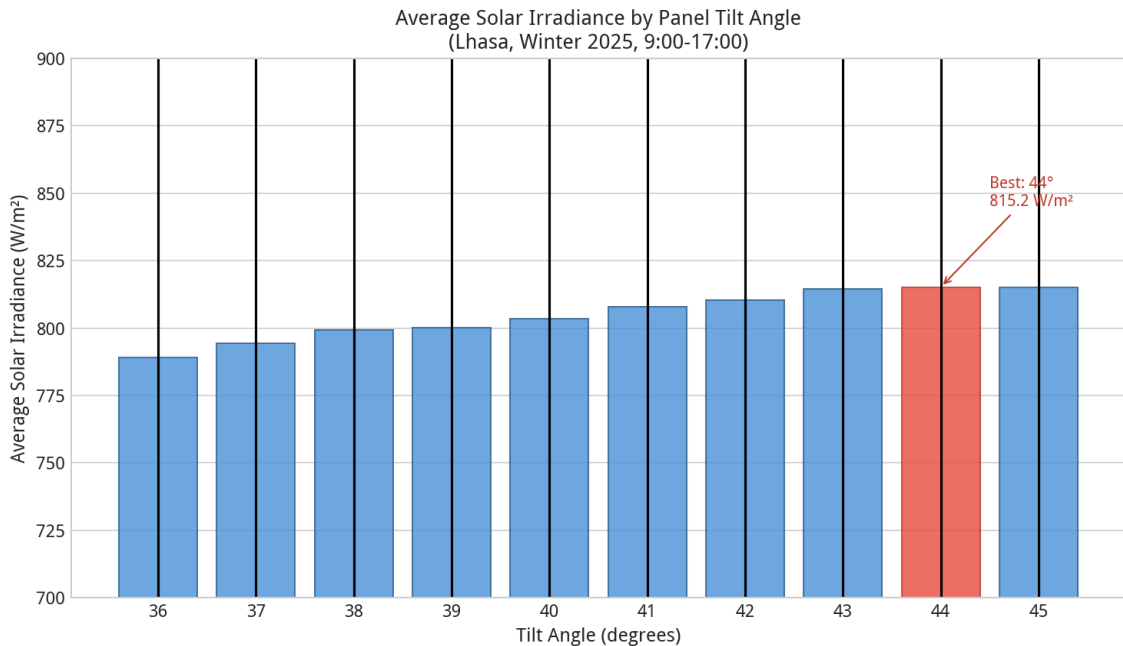


Figure 1. Average solar irradiance as a function of panel tilt angle in Lhasa during winter 2025. Error bars represent standard deviation. The red bar indicates the optimal tilt angle.

Table 1. Statistical Summary of Solar Irradiance by Tilt Angle

Tilt Angle (°)	Mean Irradiance (W/m ²)	Std Dev (W/m ²)	Maximum (W/m ²)	Minimum (W/m ²)
36	789.0	336.9	1160	176
37	794.4	338.1	1167	180
38	799.2	342.8	1191	181
39	800.3	341.4	1196	181
40	803.4	336.9	1192	201
41	807.9	335.1	1189	196
42	810.4	336.7	1191	190
43	814.5	335.5	1194	204
44	815.2	334.5	1196	206
45	815.0	334.6	1204	199

As shown in Table 1 and Figure 1, the average irradiance increases gradually with tilt angle from 36° to 44°, reaching a peak at 44° with an average irradiance of 815.2 W/m². The 45° tilt angle shows a very slight decrease to 815.0 W/m²,

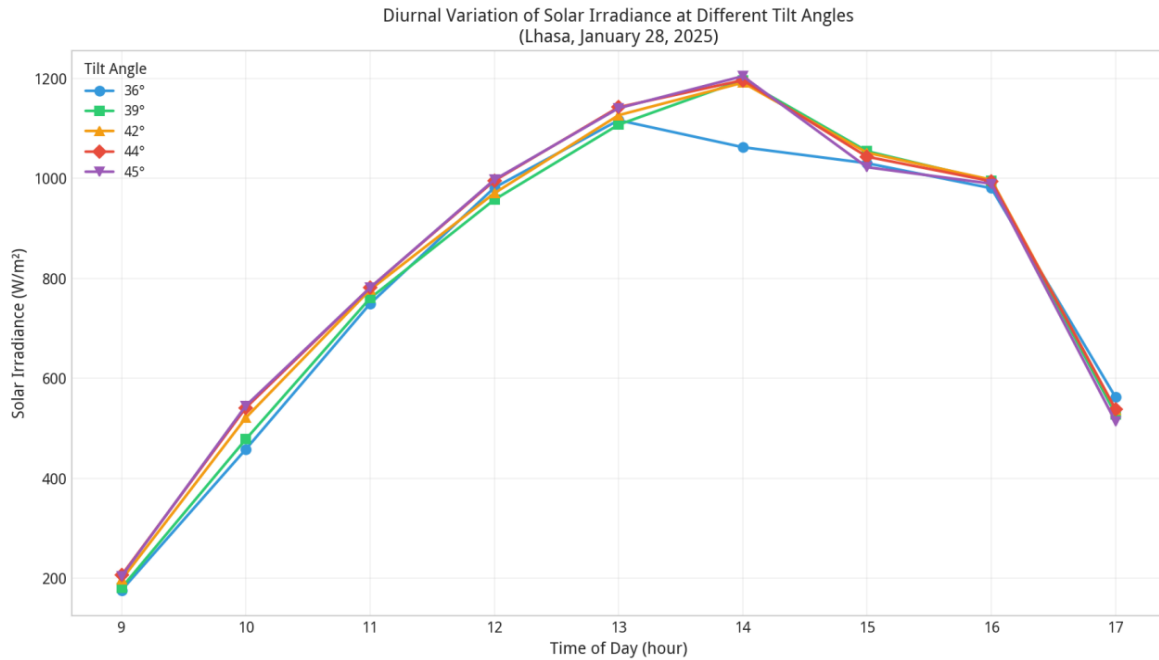
essentially equal to the 44° value within measurement uncertainty.

The overall difference between the lowest (36°: 789.0 W/m²) and highest (44°: 815.2 W/m²) performing tilt angles is 26.2 W/m², representing a 3.3% improvement. This relatively modest difference suggests that the optimal tilt angle range is quite broad, with angles between 41° and 45° all providing average irradiance above 800 W/m².

The standard deviation values are consistently around 335–343 W/m² across all tilt angles, reflecting the large diurnal variation in irradiance from early morning to midday. The maximum recorded irradiance across all measurements was 1204 W/m² at 45° tilt angle, while the minimum was 176 W/m² at 36° during the 9:00 measurement.

3.2. Diurnal Variation of Solar Irradiance

The diurnal pattern of solar irradiance at different tilt angles is illustrated in Figure 2, using data from January 28, 2025, as a representative day.

**Figure 2.** Diurnal variation of solar irradiance at selected tilt angles (36°, 39°, 42°, 44°, 45°) on January 28, 2025.

Several key observations can be drawn from the diurnal variation analysis:

(1) Symmetric bell curve pattern: The irradiance follows a roughly symmetric bell-shaped curve throughout the day, with minimum values in the early morning (9:00) and late afternoon (17:00), and peak values around midday.

(2) Peak irradiance timing: The peak irradiance occurs between 13:00 and 14:00 for most tilt angles, which is slightly after solar noon. This delay can be attributed to the difference between local solar time and Beijing standard time (UTC+8), as well as atmospheric effects.

(3) Morning rise: From 9:00 to 13:00, irradiance increases steadily as the sun rises in the sky. The rate of increase is most pronounced between 9:00 and 11:00.

(4) Afternoon decline: From 14:00 to 17:00, irradiance

gradually decreases. The decline accelerates significantly after 16:00 as the sun approaches the horizon.

(5) Tilt angle effect varies by time of day: In the early morning and late afternoon, steeper tilt angles (42°–45°) tend to show higher irradiance than shallower angles (36°–39°). Around midday, the differences between tilt angles become much smaller, as the sun is high in the sky and the angle of incidence is less sensitive to panel tilt.

3.3. Daily Total Irradiation

The daily total solar irradiation, which represents the cumulative energy received per unit area over the measurement period (9:00–17:00), is shown in Figure 3 and Table 2.

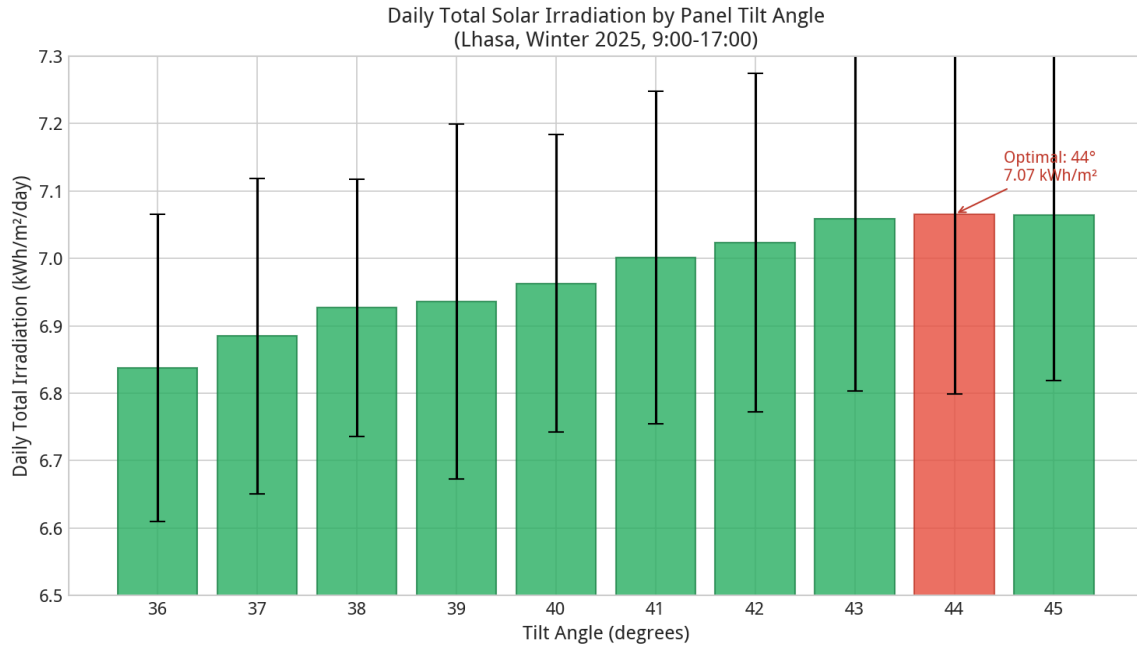


Figure 3. Daily total solar irradiation by panel tilt angle, averaged over three winter days in Lhasa. Error bars represent standard deviation across the three days.

Table 2. Daily Total Irradiation by Tilt Angle

Tilt Angle (°)	Daily Total (kWh/m ² /day)	Std Dev (kWh/m ² /day)	Relative to Optimal
36	6.84	0.23	96.7%
37	6.88	0.23	97.3%
38	6.93	0.19	98.0%
39	6.94	0.26	98.2%
40	6.96	0.22	98.4%
41	7.00	0.25	99.0%
42	7.02	0.25	99.3%
43	7.06	0.26	99.9%
44	7.07	0.27	100.0%
45	7.06	0.25	99.9%

The daily total irradiation follows a similar pattern to the average irradiance, with the maximum value of 7.07 kWh/m²/day occurring at 44° tilt angle. The 45° tilt angle is

nearly identical at 7.06 kWh/m²/day.

It is noteworthy that even the lowest-performing tilt angle (36°) achieves 96.7% of the optimal daily total, confirming that the performance curve is relatively flat around the optimum. This means that small deviations from the optimal angle (within $\pm 3^\circ$) result in less than 2% energy loss, providing flexibility in practical installation scenarios.

The standard deviation of daily totals across the three measurement days ranges from 0.19 to 0.27 kWh/m²/day, indicating consistent day-to-day irradiance conditions during the measurement period. This consistency is expected given the stable clear-sky winter conditions in Lhasa.

3.4. Morning vs. Afternoon Comparison

A comparison of morning (9:00–12:00) and afternoon (13:00–17:00) average irradiance values across all tilt angles is presented in Figure 4.

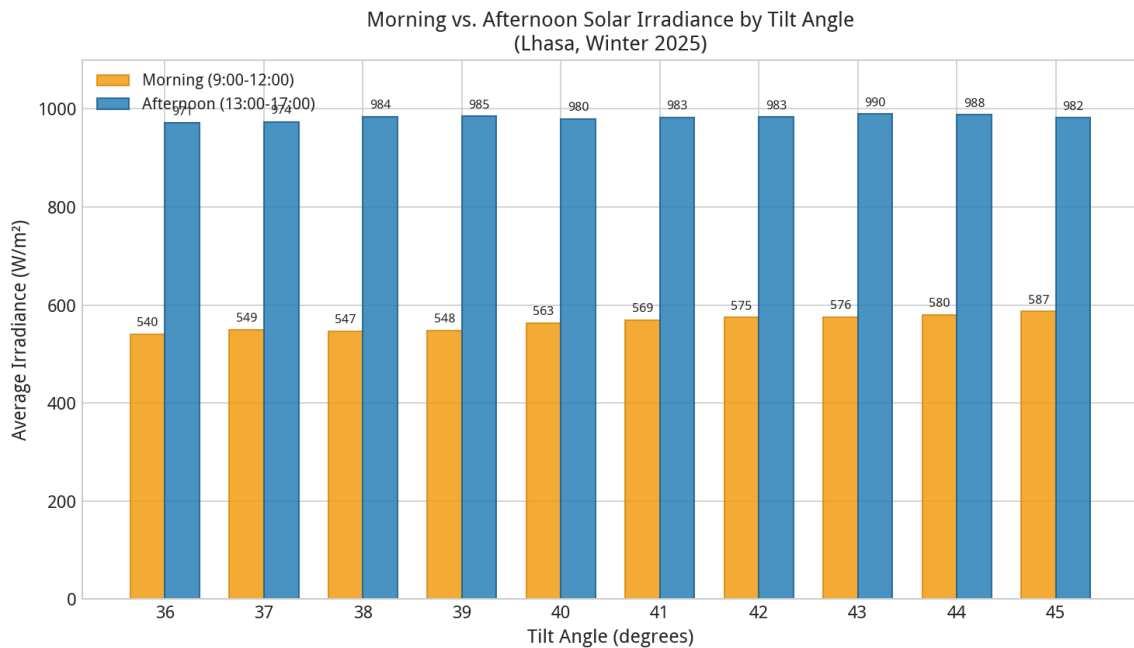


Figure 4. Comparison of average morning (9:00–12:00) and afternoon (13:00–17:00) solar irradiance by tilt angle.

The analysis reveals a significant morning-afternoon asymmetry in solar irradiance:

(1) Afternoon dominance: Afternoon irradiance is consistently and substantially higher than morning irradiance for all tilt angles. On average, afternoon irradiance is approximately 78% higher than morning irradiance.

(2) Magnitude of difference: For the optimal 44° tilt angle, morning average irradiance is approximately 580 W/m^2 , while afternoon average irradiance reaches approximately 980 W/m^2 .

(3) Tilt angle effect on asymmetry: The morning-afternoon difference is slightly more pronounced at steeper tilt angles. At 36° , the afternoon-to-morning ratio is about 1.80, while at 45° it increases to approximately 1.86.

This morning-afternoon asymmetry can be attributed to several factors:

(1) Atmospheric conditions: Morning fog or low-level clouds may reduce early morning irradiance, while afternoons tend to be clearer in the plateau climate.

(2) Solar position: In winter, the sun rises in the southeast and sets in the southwest. The south-facing panels receive more direct radiation in the afternoon when the sun is in the southwestern sky.

(3) Time zone effect: Lhasa is located in the western part of China but follows Beijing time (UTC+8), causing solar noon to occur around 13:30–14:00 local clock time rather than 12:00.

3.5. Day-to-Day Variability

The consistency of irradiance patterns across the three measurement days at the optimal 44° tilt angle is shown in Figure 5.

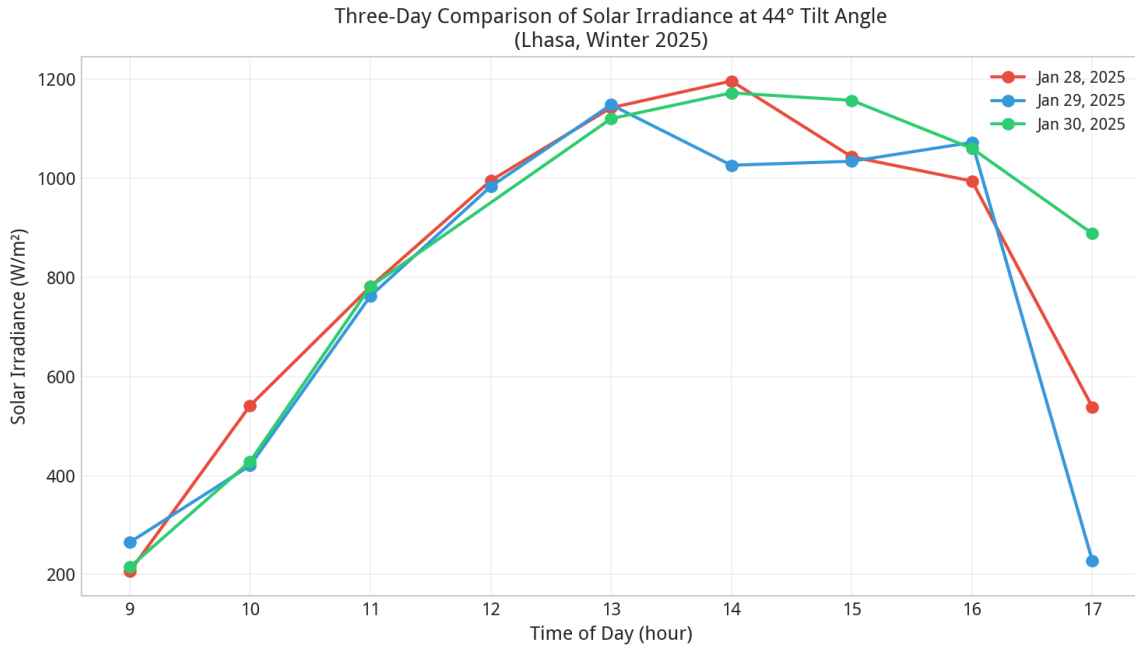


Figure 5. Comparison of diurnal irradiance patterns at 44° tilt angle across three consecutive winter days (January 28–30, 2025).

The three-day comparison demonstrates:

(1) High consistency: The diurnal patterns are remarkably similar across all three days, with peak irradiance values clustering around $1150\text{--}1200 \text{ W/m}^2$.

(2) Minor variations: Small day-to-day differences are observed, likely due to subtle variations in atmospheric conditions, aerosol content, and water vapor. January 30 shows slightly higher midday irradiance compared to the other two days.

(3) Reliable patterns: The consistent shape and magnitude of the irradiance curves across days confirm the stability of winter solar conditions in Lhasa and validate the representativeness of the measurement period.

The coefficient of variation (CV) for daily total irradiation across the three days ranges from 2.7% to 3.8% across different tilt angles, indicating low variability and high confidence in the results.

4. Discussion

4.1. Optimal Tilt Angle and Latitude Relationship

The finding that the optimal winter tilt angle in Lhasa is approximately 44° , which is about 14° steeper than the local latitude of 29.65°N , is consistent with established solar

engineering principles. For winter-optimized PV systems, the recommended tilt angle is typically latitude $+ 15^\circ$ to maximize winter energy production [7]. Our result of latitude $+ 14.35^\circ$ falls well within this expected range.

However, it is important to note that this study focused exclusively on winter conditions. For year-round energy production, the optimal tilt angle would likely be closer to the latitude angle. Many PV system designers choose a compromise angle that balances summer and winter performance, typically around latitude $\pm 5^\circ$ [8]. For Lhasa, a year-round optimal angle might be in the range of $30^\circ\text{--}35^\circ$, which would sacrifice some winter output but improve summer performance.

4.2. High-Altitude Considerations

The high elevation of Lhasa (3,656 m) has significant implications for solar irradiance that may influence optimal tilt angle:

(1) Enhanced direct irradiance: The thinner atmosphere at high altitude reduces scattering and absorption of direct solar radiation, resulting in higher direct normal irradiance (DNI) [9]. This tends to favor tilt angles that better align with the direct beam, which is consistent with our finding of a relatively well-defined optimum.

(2) Diffuse fraction: Despite the high altitude, the diffuse

fraction of solar radiation may still be significant due to the large sky view at plateau locations. Diffuse radiation is more uniformly distributed across the sky dome, which would tend to flatten the irradiance-vs-tilt-angle curve. Our observation of a relatively broad optimum (only 3.3% difference across 36°–45°) is consistent with a non-negligible diffuse component.

(3) Albedo effect: Snow cover during winter increases ground albedo, enhancing reflected radiation from below. Steeper tilt angles can capture more of this reflected radiation, which may partially explain why steeper angles perform well. However, since our measurements were taken on an urban rooftop with limited snow cover on the immediate surroundings, the albedo effect may be less pronounced than in open snowy areas.

4.3. Practical Implications for PV Installation

The results of this study have several practical implications for solar PV installation in Lhasa:

(1) Recommended winter tilt angle: For PV systems designed to maximize winter energy production, a tilt angle of 44° is recommended. However, angles between 41° and 45° all perform within 1% of the optimum, providing significant installation flexibility.

(2) Year-round systems: For grid-connected systems aiming for maximum annual energy yield, a tilt angle around 30°–35° may be more appropriate, as it would better balance summer and winter performance. Further research covering all seasons is needed to confirm the annual optimal angle.

(3) Building integration: For building-integrated PV (BIPV) applications where architectural constraints limit tilt angle adjustment, the broad optimum range means that even suboptimal angles can still achieve 95%+ of maximum performance.

(4) Afternoon bias consideration: The significant afternoon irradiance advantage suggests that PV systems with a slight westward azimuth tilt might capture more energy in Lhasa's winter climate. However, this would need to be balanced against morning performance and is beyond the scope of the current study.

4.4. Comparison with Previous Studies

Previous studies on optimal tilt angles in the Tibetan Plateau have reported varying results. A study by Li et al. [10] using modeled data suggested an optimal winter tilt angle of approximately 40°–45° for the Lhasa region, which is consistent with our field measurements. Another study focusing on the Qinghai-Tibet Plateau recommended tilt angles of 40°–50° for winter optimization [11]. Our field-measured value of 44° falls within the range predicted by these modeling studies, providing empirical validation.

The daily total irradiation values of 6.84–7.07 kWh/m²/day (measured from 9:00 to 17:00) are also consistent with reported winter values for the Lhasa region. The Tibet Solar Energy Resources Assessment Report [12] indicates January average daily global horizontal irradiation of approximately 5.5–6.0 kWh/m²/day for Lhasa. Our tilted-surface values being higher than horizontal values is expected, as optimized tilt angles always capture more radiation than horizontal surfaces in winter.

4.5. Limitations of the Study

Several limitations should be acknowledged:

(1) Limited measurement period: The study covers only

three days in January. While the clear-sky conditions ensure data quality, a longer measurement period would provide more robust statistics and capture a wider range of weather conditions.

(2) Winter-only data: The results are specific to winter conditions. A comprehensive assessment of optimal tilt angle would require data from all seasons.

(3) Clear-sky bias: All measurement days were clear-sky days. Cloudy or partially cloudy conditions might shift the optimal tilt angle, as diffuse radiation distribution differs from direct beam radiation.

(4) Single location: The measurements were taken at a single urban rooftop site. Results might vary slightly at different locations within the Lhasa area due to variations in elevation, surrounding terrain, and local microclimate.

(5) Measurement time window: Data were collected only from 9:00 to 17:00. Including early morning and late afternoon measurements would provide a more complete picture of daily total irradiation.

5. Conclusion

This study presents a field investigation of the optimal tilt angle for solar PV panels in Lhasa, Tibet, during winter. Based on irradiance measurements at ten tilt angles (36°–45°) over three clear-sky days in January 2025, the following conclusions can be drawn:

(1) Optimal tilt angle: The 44° tilt angle provides the highest average irradiance (815.2 W/m²) and the highest daily total irradiation (7.07 kWh/m²/day) among the tested angles. This is approximately 14° steeper than the local latitude, consistent with the principle that winter-optimized tilt angles exceed latitude.

(2) Broad optimum range: The performance curve is relatively flat around the optimum, with tilt angles from 41° to 45° all achieving average irradiance above 800 W/m² and within 1% of the maximum. This provides practical flexibility for PV installation.

(3) Morning-afternoon asymmetry: Afternoon irradiance is significantly higher than morning irradiance across all tilt angles, with peak values occurring between 13:00 and 14:00. This pattern is influenced by the time zone offset and local atmospheric conditions.

(4) High-altitude solar resource: The high irradiance values (peak exceeding 1200 W/m², daily totals around 7 kWh/m²) confirm Lhasa's exceptional solar energy potential during winter, supporting the rapid development of solar power in the region.

(5) Practical recommendations: For winter-optimized PV systems in Lhasa, a tilt angle of 44° is recommended. For year-round systems, a compromise angle in the range of 30°–35° may be more appropriate, though further seasonal data are needed to confirm this.

Future research should expand the measurement period to cover all seasons, include diffuse and direct radiation components, and investigate the effects of azimuth angle and albedo on tilted-surface irradiance. Such studies will contribute to the optimization of solar energy systems and the sustainable development of the Tibetan Plateau.

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