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Simulation-Based Assessment of Tilt Angle Influence on Standalone Solar PV Performance

Hawa Singh [1], Digpratap Singh [2]
[1]Department of Physics, C. L. Jain College, Firozabad-283203, Dr. Bhimrao Ambedkar University, Agra-282002 (UP) India
[2]Department of Physics, Narain College, Shikohabad, Firozabad- 283135, Dr. Bhimrao Ambedkar University, Agra-282002 (UP) India
[1]**Corresponding Author**: hawasingh_saant@yahoo.com

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Abstract

This paper presents a simulation-based analysis of the effect of tilt angle on the performance of a 14.08 kWp standalone photovoltaic (PV)–battery system designed to meet a constant 2 kW electrical load at Narain College, Shikohabad, Uttar Pradesh, India. Using PVsyst 7.4 with meteorological inputs from Meteonorm 8.1, the system was modeled with 32 monocrystalline 440 Wp modules and a lead-acid battery bank (96 V, 2400 Ah; 184.3 kWh storage). Simulations were carried out for tilt angles ranging from 5° to 35° while keeping azimuth fixed at 0° (south-facing). Key performance metrics included annual useful energy, missing load, excess/unused energy, performance ratio (PR), solar fraction (SF), and specific yield. The results indicate that tilt angle significantly influences system reliability and energy yield. The optimal tilt angle was found to be 25°, corresponding closely to the site's latitude (27.1°N). At this configuration, the system achieved the highest useful energy output (17,094 kWh/year), lowest missing load (426 kWh/year), and peak specific yield (1214 kWh/kWp), with a PR of ~70% and SF of 97.6%. However, substantial unused energy (~12% of generation) was observed, underscoring the need for optimized storage and load management. The study highlights tilt angle optimization as a low-cost strategy for enhancing standalone PV–battery performance in rural Indian contexts.

Keywords: *PVsyst simulation, Standalone PV–battery system, Tilt angle optimization, Solar fraction and performance ratio, Renewable energy in India*

1. Introduction

Solar photovoltaic (PV) systems have emerged as one of the fastest-growing renewable energy technologies due to their scalability, modularity, and declining costs [1], [2].Photovoltaic (PV) systems are experiencing widespread adoption due to their potential for clean, renewable energy generation. A key determinant of PV performance is the tilt angle of the solar modules. Studies have demonstrated that module tilt significantly impacts incident irradiance, module temperature, and overall power output. For example, Al-Waeli et al. (2017) found that increasing tilt enhanced irradiance and power but also raised module temperature, which in turn affected voltage and current characteristics [3]. Similarly, Ebhota and Tabakov (2022) utilized PVsyst to conclude that a 40° tilt at an East-West azimuth (0° deviation) delivered optimal energy yield, specific energy, used energy, solar fraction, and minimized losses in a standalone c-Si PV system in Durban, South Africa [4].

In standalone PV-battery systems, tilt optimization must balance energy generation and load reliability. Electrical designers often aim to maximize "usable" or "useful" energy delivered to the load while minimizing unmet demand and excess waste. Tuama et al. (2021) reported that a fixed 30° tilt in Baghdad yielded the best annual performance, although even modest seasonal configuration adjustments or tracking systems provided further gains (~5% and ~25% respectively) [5]. These findings highlight the significance of tilt angle optimization in enhancing system resilience and efficiency, particularly for off-grid applications.

In recent years, numerous studies have evaluated the effect of tilt angle on photovoltaic performance under diverse climatic conditions. For instance, Bakirci (2012) investigated optimum tilt angles for PV modules in Erzurum, Turkey, and reported seasonal variations of up to 15% in energy yield depending on module inclination [6]. Jacobson and Jadhav (2018) highlighted that improper tilt configuration in large-scale solar parks in India can reduce energy output by more than 10% annually [7]. More recently, Ebhota and Tabakov (2022) demonstrated, using PVsyst, that tilt and azimuth optimization significantly enhance solar fraction and minimize load mismatch in standalone systems [4]. Such findings underscore the importance of site-specific tilt optimization, especially in off-grid PV–battery applications in regions with distinct seasonal irradiance profiles.

This study presents a PVsyst-based simulation of a 14.08 kWp off-grid PV–battery system in Shikohabad, India, exploring tilt variations from 5° to 35°. By examining metrics such as annual useful energy, missing load, performance ratio, solar fraction, and specific yield, the paper seeks to identify the optimal tilt for maximizing system performance in this specific rural Indian context. The results are expected to provide insights into improving standalone PV design in similar climatic regions.

2. Simulation Methodology

The performance analysis of the standalone photovoltaic (PV) system was conducted using PVsyst version 7.4, a widely validated simulation tool for PV system modeling and energy yield assessment [8]. The study site was Narain College, Shikohabad, Firozabad, Uttar Pradesh, India (27.11°N, 78.58°E; 159 m altitude). Climatic data were obtained from Meteonorm 8.1 (1996–2015) synthetic database integrated into PVsyst, which provides long-term average irradiance and temperature profiles [9]. The general simulation input conditions, including site details and load profile, are summarized in Table 1.

The system modeled is a 14.08 kWp standalone PV–battery installation designed to supply a constant load of 2 kW (17.52 MWh/year). The PV array was configured with 32 monocrystalline 440 Wp twin half-cell modules in 8 strings of 4 modules each, with module parameters provided in Table 2. The energy storage is provided by a lead-acid battery bank (96 V, 2400 Ah; 184.3 kWh capacity) configured as 24 units in parallel and 8 in series. Detailed specifications of the battery subsystem are presented in Table 3. Battery charge and discharge processes were simulated with round-trip efficiency, self-discharge, and gassing losses considered, as recommended in previous PVsyst-based studies [10].

To evaluate the effect of tilt angle on energy yield, simulations were performed for seven tilt configurations (5°, 10°, 15°, 20°, 25°, 30°, and 35°) with azimuth fixed at 0° (south-facing). The orientation details and tilt angle variations are listed in Table 4. For each case, the software generated energy balances including useful energy supplied to the load, missing load, excess/unused energy, performance ratio (PR), solar fraction (SF), and specific yield. Loss diagrams were also analyzed to quantify irradiance, temperature, wiring, and storage-related losses.

Table 1. General System Input Parameters

Parameter	Value
Location	Shikohabad, India (27.11°N, 78.58°E)
Simulation tool	PVsyst 7.4
Meteo data source	Meteonorm 8.1 (1996–2015)
Load profile	Constant 2 kW
Annual load demand	17.52 MWh

Table 2. PV Array Specifications

Parameter	Value
Module type	Mono 440 Wp, 144 half-cells
Number of modules	32 (8 strings × 4 modules)
Array nominal capacity	14.08 kWp
Nominal efficiency (STC)	19.8%
Array area	71.2 m^2

Table 3. Battery Specifications

Parameter	Value
Technology	Lead-acid, vented plates
Configuration	24 in parallel × 8 in series
Bank voltage	96 V
Capacity	2400 Ah (C10)
Stored energy	~184.3 kWh
Minimum SOC	20%

Table 4. Orientation and Tilt Configurations

Parameter	Value(s) Tested
Orientation	Fixed tilt, South (0° azimuth)
Tilt angles	5°, 10°, 15°, 20°, 25°, 30°, 35°

3. Results and Discussion

3.1 Annual Energy Yield and System Performance

The annual simulation results for different tilt angles (5°–35°) are summarized in Table 5. The useful energy delivered to the load increased steadily from 16,642 kWh at 5° to a maximum of 17,094 kWh at 25°, after which it declined slightly at higher tilts (30°–35°). This indicates that 25° is the optimal tilt angle for the Shikohabad site, consistent with the site's latitude

(27.1°N). Prior studies also report that the optimal fixed tilt angle for PV modules is generally close to the latitude of the location [7].

Table 5. Summary of annual simulation results for different tilt angles

Tilt (°)	Useful Energy (kWh/yr)	Missing Energy (kWh/yr)	Excess/Unused (kWh/yr)	PR (%)	SF (%)	Specific Yield (kWh/kWp)
5	16,642.7	877.3	1,757.9	71.1	95.0	1182
10	16,891.2	628.8	1,876.0	70.8	96.4	1200
15	17,053.9	466.1	1,971.6	70.5	97.3	1211
20	17,060.6	459.4	2,078.4	70.0	97.4	1212
25	17,094.1	425.9	2,069.0	70.0	97.6	1214
30	17,070.1	449.9	2,006.5	70.1	97.4	1212
35	17,028.5	491.5	1,914.4	70.6	97.2	1209

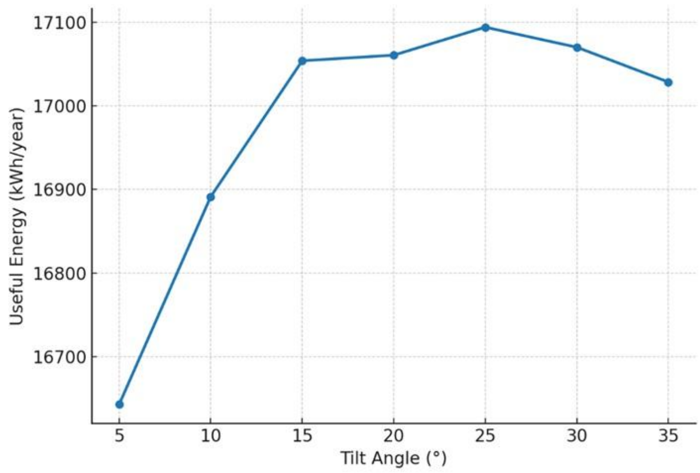

Fig. 1. Variation of annual useful energy with tilt angle.

The variation of useful energy with tilt angle is also illustrated in Figure 1, where a clear maximum is observed at 25°. Beyond this tilt, the energy yield decreases slightly due to reduced incident irradiation during summer months, as also reported in similar studies for Indian and Middle Eastern climates [3], [5], [11].

3.2 Load Coverage and Reliability

The extent to which the system can meet the prescribed constant 2 kW load is a critical measure of reliability in standalone PV–battery systems. As shown in Table 5, the missing energy was maximum at 877 kWh/year (5% of demand) for a shallow tilt of 5°. This reflects underperformance during the winter months, when the sun's elevation is lower and flatter modules collect less irradiance. Increasing the tilt improves capture of winter solar energy, leading to a steady decline in missing energy. At 25° tilt, the missing energy dropped to just 426 kWh/year (2.4% of demand), marking the best system reliability among all configurations.

Beyond 25°, however, the missing energy begins to rise again (492 kWh/year at 35°). This is attributed to reduced energy capture in the summer months when the higher tilt angles are less aligned with the sun's path. A similar seasonal mismatch was observed by Tuama et al. (2021), who reported that fixed tilt systems in Iraq underperformed in summer at high inclinations, necessitating either seasonal adjustments or tracking mechanisms [5]. Comparable findings have also been documented in Bangladesh and Kenya [12], [13].Therefore, while the system is capable of supplying over 97% of annual demand at optimal tilt, residual shortfalls may still require backup or demand-side management.

3.3 Excess and Unused Energy

Another important performance indicator is the excess or unused energy, representing the electricity generated by the PV array that could not be consumed or stored due to battery saturation. As shown in Table 5, the excess energy increased with tilt angle, rising from ~1,758 kWh at 5° to ~2,069 kWh at 25°. This trend indicates that while higher tilts enhance annual production, they also create periods of over-generation relative to storage and load demand.

Unused energy is a common issue in standalone PV systems, particularly when storage is sized conservatively for economic reasons [14]. In this case, the battery bank capacity of ~184 kWh was sufficient to buffer diurnal fluctuations but could not absorb sustained surpluses during high-irradiance months. The issue is most pronounced in May–June, when solar irradiation peaks. Similar results have been documented by Sharma et al. (2015), who reported excess energy losses of 5–15% in off-grid Indian systems [15].

Addressing this challenge requires either (a) expanding battery capacity, (b) integrating load-shifting strategies, or (c) hybridization with auxiliary systems to utilize otherwise wasted energy. For example, Jacobson and Jadhav (2018) suggested that coupling solar PV with water pumping or thermal storage can increase the effective utilization of excess generation.

3.4 Performance Ratio and Specific Yield

The performance ratio (PR) remained relatively stable across tilt angles, ranging between 69.9% and 71.1% (Table 5). The slight decline observed beyond 20° tilt is attributed to increased seasonal mismatch and greater storage-related losses. PR values above 70% indicate a well-performing standalone PV system, aligning with international benchmarks reported for tropical climates [16].

The specific yield — a normalized measure of system output — peaked at 1214 kWh/kWp at 25° tilt. This is consistent with the optimal tilt yielding the highest irradiance capture relative to system capacity. As shown in Figure 2, the curve of specific yield vs. tilt angle mirrors that of useful energy, reinforcing the conclusion that 25° is the optimal configuration for the Shikohabad site.

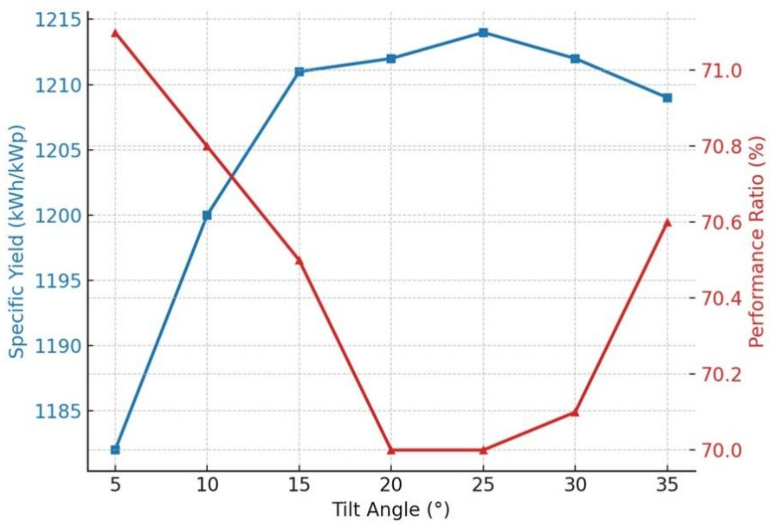

Fig. 2. Variation of specific yield and performance ratio (PR) with tilt angle.

3.5. Comparative Discussion and Implications

The simulations clearly indicate that 25° tilt provides the best compromise between maximizing annual energy yield, minimizing missing energy, and maintaining a high solar fraction. This result is intuitively consistent with the site's latitude (27°N), validating empirical guidelines for tilt selection [7]. However, the relatively small differences between 20°, 25°, and 30° tilts suggest that the system is not highly sensitive within this range, which provides some design flexibility in rooftop or ground-mounted installations.

Nevertheless, the issue of unused energy remains a limitation. At optimal tilt, nearly 12% of annual generation was curtailed due to insufficient storage or load absorption. This finding echoes observations from Bala & Siddiqui (2012), who reported similar curtailment in standalone systems, leading to reduced overall efficiency [14]. Future system improvements could focus on:

- Enhanced storage solutions, such as lithium-ion batteries, which offer higher round-trip efficiencies and longer lifetimes compared to lead-acid.
- Hybrid system design, where excess PV generation can be redirected for productive end-uses such as water pumping, heating, or community microgrids.
- Dynamic tilt or tracking systems, which Tuama et al. (2021) reported to improve yields by up to 25%, albeit at higher capital cost [5].

From a broader perspective, the results underscore the importance of site-specific system optimization. While empirical latitude-based tilt rules provide good first-order estimates, detailed simulation studies are necessary to account for climatic variability, load profiles, and storage dynamics. This is particularly relevant for rural Indian contexts, where standalone PV–battery systems are deployed for educational, health, and community facilities.

4. Conclusion

This study investigated the effect of tilt angle on the performance of a 14.08 kWp standalone PV–battery system located in Shikohabad, Uttar Pradesh, using PVsyst 7.4 simulations. The results demonstrated that tilt angle strongly influences annual energy yield, load coverage, and system reliability. Among the simulated configurations (5°–35°), the optimal tilt angle was identified as 25°, which provided the highest useful energy output (17,094 kWh/year), lowest missing load (426 kWh/year), maximum solar fraction (97.6%), and peak specific yield (1214 kWh/kWp). These results align with the empirical guideline that optimal fixed tilt angles are close to the site latitude [7], [17]. Despite the favorable performance, the system exhibited significant unused energy (~12% of annual production), primarily due to battery saturation during high irradiance months. This highlights the importance of holistic system optimization, including storage sizing, demand management, and hybridization strategies, to maximize energy utilization [14], [18], [19]. Future work should explore advanced battery technologies (e.g., lithium-ion or flow batteries) with higher efficiencies and deeper cycling capabilities to reduce curtailment [13], [20]. Additionally, hybrid systems combining PV with productive loads (e.g., water pumping, heating, or microgrid applications) could improve energy utilization [21], [22]. Finally, seasonal tilt adjustments or low-cost tracking systems may be considered to further enhance yield, as prior studies have shown potential gains of 5–25% [5], [23]. These improvements will be crucial in designing resilient, efficient, and economically viable standalone PV–battery systems for rural electrification in India and similar regions [24], [25].

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