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Chapter

Altitude-Based Solar PV Sustainability Assessment in Una District, Himachal Pradesh

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ABSTRACT

Rural energy planning in mountainous regions requires an accurate assessment of photovoltaic (PV) system sustainability under varying climatic conditions. However, existing studies primarily focus on solar resource assessment or system performance, with limited attention to how altitude-driven climatic variations influence lifecycle metrics such as Energy Payback Time (EPBT) at a micro-regional scale. This study addresses this gap by evaluating the influence of altitude on PV performance and EPBT across selected locations in Una district, Himachal Pradesh.

A uniform grid-connected PV system configuration was simulated using PVsyst, with site-specific meteorological inputs derived from Meteonorm. All system parameters were held constant across locations to isolate the effect of altitude-dependent variables, particularly ambient temperature and solar irradiance. Annual energy output and specific yield were computed, and EPBT was estimated using a constant, literature-based embodied energy assumption.

Results indicate a measurable but moderate variation (~3–4%) in PV performance across the studied altitude range, primarily attributed to temperature-induced efficiency differences rather than substantial changes in solar irradiance. Correspondingly, EPBT shows a slight reduction at higher elevations due to increased energy generation. However, the magnitude of this improvement remains limited, indicating that altitude alone is not a dominant factor influencing lifecycle sustainability within the selected range.

The findings demonstrate that altitude-related performance gains are incremental rather than transformative, emphasising that PV site selection in mountainous regions should consider broader factors beyond elevation. The study provides a controlled, district-level assessment linking altitude to EPBT, contributing empirical evidence for more realistic and context-specific solar deployment planning in Himalayan regions.

Keywords: *Photovoltaic Systems, Energy Payback Time (EPBT), Altitude Effects, Mountainous Regions, Solar Energy, Rural Energy Planning*

INTRODUCTION

Photovoltaic (PV) systems are increasingly adopted as decentralised energy solutions in mountainous regions, where conventional grid expansion is constrained by terrain and infrastructure limitations. However, the long-term sustainability of PV deployment depends not only on energy generation but also on lifecycle performance indicators such as Energy Payback Time (EPBT), which reflects the time required for a system to recover its embodied energy.

In regions such as Himachal Pradesh, PV system performance is influenced by spatial variations in climatic conditions, particularly solar irradiance and ambient temperature. These parameters are strongly linked to altitude, which governs atmospheric transparency, thermal conditions, and local microclimates. While lower temperatures at higher elevations can enhance PV efficiency, variations in solar radiation due to cloud cover, terrain effects, and atmospheric conditions may offset these gains. As a result, the net influence of altitude on PV performance remains uncertain and site-dependent. Previous studies in the Himalayan region have primarily focused on solar resource assessment or hybrid energy system feasibility. However, these studies often involve variations in system configuration, input assumptions, and site conditions, limiting their ability to isolate the independent effect of altitude on PV performance. Consequently, the extent to which altitude alone influences PV energy output remains insufficiently understood, particularly at the district or micro-regional scale.

In addition, the relationship between altitude-driven performance variation and lifecycle metrics such as EPBT has received limited attention. Existing EPBT analyses are typically based on generalized assumptions or large-scale studies, which do not capture localized variations relevant for decentralized energy planning. This gap is particularly important in regions such as Una district, where moderate altitude variation exists but its practical impact on PV performance and energy recovery has not been systematically evaluated.

To address these limitations, the present study adopts a controlled simulation-based approach using PVsyst. A uniform PV system configuration is applied across multiple locations within Una district, while only altitude-dependent climatic parameters are allowed to vary. This enables isolation of the effect of altitude on annual energy output, specific yield, and EPBT. The study provides a localised and methodologically consistent assessment of whether altitude-driven variations are significant enough to influence PV deployment decisions in mountainous regions.

METHODOLOGY

Study Area and Site Selection

The study is conducted in Una district, Himachal Pradesh, India, characterised by a moderate altitude range (~350–950 m) within a confined geographical area. Six locations-Pandoga, Una, Mehatpur, Gagret, Amb, and Chintpurni-were selected to represent low-, mid-, and high-altitude zones. These locations correspond to major population centres and surrounding rural clusters, ensuring practical relevance for decentralised PV deployment. Their geographic coordinates and elevations are provided in Table 1. The selection within a single district minimises large-scale climatic variability, enabling focused assessment of altitude-associated climatic effects on PV performance.

Table 1. Geographical Coordinates of Selected Locations

Location	Latitude (°N)	Longitude (°E)	Altitude (m)
Pandoga	31.42	76.28	~350
Una	31.47	76.26	379
Mehatpur	31.45	76.25	385
Gagret	31.66	76.06	465
Amb	31.69	76.12	468
Chintpurni	31.86	76.32	~936

PV System Configuration and Simulation Setup

A uniform grid-connected photovoltaic (PV) system with an installed capacity of 14.82 kWp was modeled in PVsyst for all selected locations. The system consists of 78 polycrystalline modules of 190 Wp each, arranged in 6 strings of 13 modules (6 × 13). The PV array is oriented due south with an azimuth angle of 0° and a fixed tilt angle of 20°, ensuring consistency across all simulations. The total inverter capacity is 12.6 kW, comprising three 4.2 kW inverters, resulting in a DC–AC ratio of approximately 1.18. Standard system losses were incorporated uniformly across all locations. Thermal behaviour was modeled using a heat loss coefficient (Uc = 20 W/m^2·K) with no wind dependency. No near-field shading losses were considered, and a free-horizon condition was assumed for all sites to maintain consistency. All system parameters were kept identical across simulations to ensure that variations in performance are attributable solely to location-specific climatic conditions.

Controlled Simulation Design

Site-specific meteorological data, including global solar irradiance and ambient temperature, were obtained from the Meteonorm database integrated within PVsyst (Sharma, 2026).. Meteonorm data were used due to the limited availability of long-term measured datasets and are widely accepted for PV performance simulations in data-scarce regions.

Simulations were conducted for each selected location using a controlled framework in which all PV system parameters were kept identical. Only climate-dependent variables-primarily solar irradiance and ambient temperature-were varied based on site-specific inputs.

This approach enables isolation of altitude-associated climatic effects on PV performance, ensuring that observed variations are not influenced by differences in system configuration or operational parameters.

Performance Metrics

PV system performance at each location was evaluated using:

- Annual Energy Output (kWh/year)
- Specific Yield (kWh/kWp/year)
- Performance Ratio (PR)

These metrics provide a standardised basis for comparing system performance across locations with identical configuration, while distinguishing between energy generation and system efficiency.

EPBT Calculation and Assumptions

The Energy Payback Time (EPBT) was calculated as:

$$EPBT = \frac{E_{embodied}}{E_{annual}}$$

where E_{annual}(kWh/year) is obtained from PVsyst simulation outputs, and E_{annual}(kWh) represents the lifecycle energy input associated with PV system production.

A constant embodied energy value was adopted from literature-reported ranges for crystalline silicon PV systems. This includes contributions from PV modules and balance-of-system (BOS) components, assumed proportional and constant due to identical system configuration across all locations.

This approach ensures that variations in EPBT are driven solely by differences in annual energy generation. While absolute EPBT values depend on embodied energy assumptions, relative comparisons across locations remain valid under consistent system conditions.

Statistical Analysis Framework

To complement the comparative assessment of photovoltaic (PV) performance across the selected locations, exploratory statistical analyses were conducted to examine the relationship between altitude and key performance indicators. Pearson correlation analysis and simple linear regression were applied using the simulated results obtained for the six study locations.

Pearson correlation analysis was employed to evaluate the strength and direction of associations among altitude, specific yield, and Energy Payback Time (EPBT). Correlation coefficients (r) range from −1 to +1, where positive values indicate direct relationships and negative values indicate inverse relationships. The analysis was used to determine whether increasing altitude was systematically associated with changes in PV performance and lifecycle energy recovery.

Table 2. Pearson Correlation Matrix for Altitude, Specific Yield, and EPBT

Variable	Altitude (m)	Specific Yield	EPBT
Altitude (m)	1.000	0.882	-0.878
Specific Yield	0.882	1.000	-0.999
EPBT	-0.878	-0.999	1.000

The correlation results indicate a strong positive association between altitude and specific yield and a corresponding strong negative association between altitude and EPBT. The near-perfect inverse relationship reflects the mathematical dependence of EPBT on annual energy generation under a constant embodied-energy assumption and should not be interpreted as an independent physical relationship. In addition, simple linear regression analysis was performed to quantify the relationship between altitude (independent variable) and specific yield (dependent variable). The general form of the regression model is:

Specific Yield = b0 + (b1 × Altitude)

where:

b0 = intercept, b1 = slope coefficient

Altitude = site elevation (m)

Specific Yield = annual PV energy production (kWh/kWp/year)

The resulting empirical relationship for the study locations was:

Specific Yield (kWh/kWp/year) = 1301.84 + (0.0691 × Altitude)

Table 3. Linear Regression Results for Altitude and Specific Yield

Parameter	Value
Number of observations (n)	6
Intercept (b0)	1301.84
Slope coefficient (b1)	0.0691
Correlation coefficient (r)	0.882
Coefficient of determination (R^2)	0.777
Yield increase per 100 m elevation gain	6.9 kWh/kWp/year

The regression results indicate a statistically significant positive relationship between altitude and specific yield ($R^2 = 0.777$). The slope coefficient suggests that specific yield increases by approximately 6.9 kWh/kWp/year for every 100 m increase in elevation within the study area. However, given the limited number of observations and the relatively narrow elevation range represented within Una district, the regression model should be interpreted as an exploratory empirical relationship rather than a broadly applicable predictive model.

All statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$). Because the analysis was based on six locations within a single district, the statistical results should be interpreted as indicative associations rather than broadly generalizable relationships

RESULTS AND DISCUSSION

Annual Energy Output

The annual energy output of the photovoltaic (PV) system was evaluated for all selected locations under an identical system configuration. The results are summarized in

Table 4. Performance Comparison Across Selected Locations

Location	Altitude (m)	Energy (kWh/year)	Specific Yield (kWh/kWp)	PR (%)	EPBT (years)*
Pandoga	~350	19431	1311	79.63	~8.02
Una	379	19784	1335	79.72	~7.80
Mehatpur	385	19770	1334	79.57	~7.81
Gagret	465	19752	1333	79.92	~7.82
Amb	468	19852	1339	~79.8	~7.75
Chintpurni	~936	20230	1365	~80.0	~7.61

**EPBT calculated using constant embodied energy assumption.*

The results indicate a gradual increase in annual energy output with elevation. The lowest energy generation is observed at Pandoga (~19431 kWh), while the highest is recorded at Chintpurni (~20230 kWh). However, the overall variation remains modest (~4%), suggesting that altitude-driven climatic differences have a limited influence on total energy generation within the studied range.

Specific Yield Analysis

Specific yield provides a normalised basis for comparing PV performance independent of system size. The results show a gradual increase in specific yield with altitude, as summarised in Table 2. Specific yield increases from 1311 kWh/kWp at Pandoga (~350 m) to 1365 kWh/kWp at Chintpurni (~936 m). Mid-altitude locations-Una (1335 kWh/kWp), Mehatpur (1334 kWh/kWp), Gagret (1333 kWh/kWp), and Amb (1339 kWh/kWp)-exhibit similar values within a narrow range of 1333–1339 kWh/kWp.

The overall variation in specific yield across the studied altitude range is approximately 4.1%, indicating a measurable but limited influence of altitude on PV performance. This trend is primarily attributed to lower ambient temperatures at higher elevations, which reduce thermal losses and improve module efficiency. In contrast, variations in solar irradiance across locations are relatively small and do not significantly alter performance trends.

Performance Ratio

The performance ratio (PR) remains nearly constant across all locations, ranging between approximately 79.5% and 80%. This minimal variation confirms that system losses and operational efficiency are consistent across simulations. The uniformity of PR indicates that differences in energy output and specific yield are not caused by system-level variations, but are driven by location-dependent climatic conditions. This supports the validity of the controlled simulation framework.

EPBT Analysis

Table 5: Energy Payback Time (EPBT) Across Selected Locations

Location	Energy (kWh)	EPBT (years)
Pandoga	19431	~7.99
Una	19784	~7.80
Mehatpur	19770	~7.81
Gagret	19752	~7.82
Amb	19852	~7.76
Chintpurni	20230	~7.61

The Energy Payback Time (EPBT) was calculated for all locations using a constant embodied energy assumption. The results indicate a gradual decrease in EPBT with increasing altitude, corresponding to higher annual energy generation. EPBT values range from approximately 7.99 years at the lowest-altitude location (Pandoga) to about 7.61 years at the highest-altitude location (Chintpurni). Mid-altitude locations exhibit similar values within a narrow range of approximately 7.76–7.82 years.

The overall variation in EPBT is modest, with a reduction of approximately 4–5% across the studied altitude range. This trend is consistent with the observed increase in specific yield, indicating that improvements in energy generation directly translate into slightly faster energy recovery. However, the magnitude of EPBT reduction remains limited, suggesting that altitude alone has a relatively small influence on lifecycle performance within the selected elevation range.

Interpretation of Altitude Influence

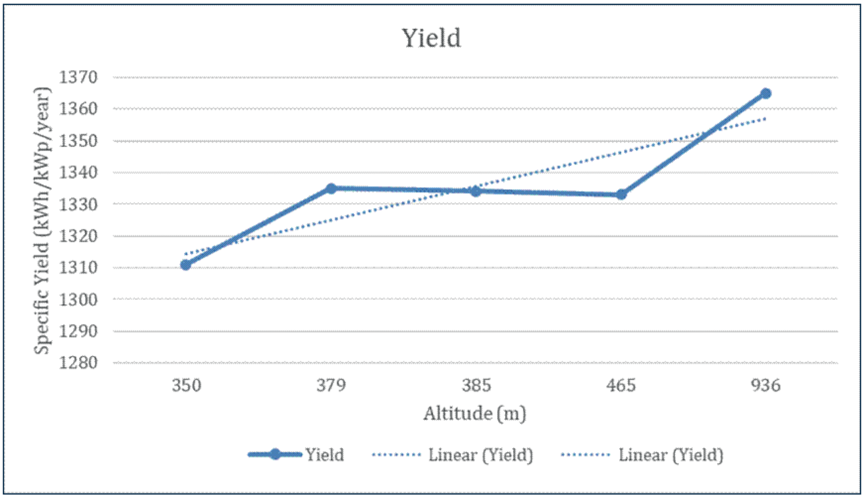

Figure 4. Relationship between Altitude and Specific Yield Across Selected Locations in Una District.

Figure 4 illustrates the relationship between altitude and specific yield across the six study locations. A positive trend is evident, indicating that photovoltaic performance generally improves with increasing elevation. The fitted regression line is consistent with the statistical results presented in Table 4, which yielded a positive slope coefficient (0.0691) and a coefficient of determination ($R^2 = 0.777$). Although the relationship is statistically significant, the relatively small number of observations and the restricted altitude range suggest that the trend should be interpreted as an exploratory empirical association rather than a broadly applicable predictive relationship.

The observed variation in PV performance across locations is primarily associated with altitude-driven changes in ambient temperature rather than significant differences in solar irradiance. As altitude increases, lower ambient temperatures reduce PV module operating temperature, leading to improved conversion efficiency and higher specific yield.

The exploratory statistical analysis supports the observed performance trend. Pearson correlation analysis indicated a strong positive association between altitude and specific yield ($r = 0.882$) and a strong negative association between altitude and EPBT ($r = -0.878$). Simple linear regression further demonstrated a statistically significant positive relationship between altitude and specific yield ($R^2 = 0.777$). Nevertheless, the relatively small sample size and restricted elevation range suggest that these results should be interpreted as supporting evidence rather than definitive predictive relationships.

In the present study, this effect results in a modest increase in specific yield from 1311 to 1365 kWh/kWp (~4.1%) across the altitude range of approximately 350 m to 936 m. The corresponding improvement in annual energy output leads to a similar reduction in EPBT (~4–5%). These findings indicate that altitude-related performance gains are directly linked to thermal effects rather than substantial variations in solar resource availability.

However, the magnitude of this improvement remains limited. The observed variation in performance is comparable to typical uncertainties associated with simulation-based assessments and system-level losses. This suggests that while altitude contributes to PV performance enhancement, its influence is secondary and does not independently drive substantial gains in system efficiency or lifecycle performance.

Implications for Rural Energy Planning

The results indicate that altitude has a measurable but limited influence on PV system performance and lifecycle metrics within the studied range. Although higher-altitude locations show slightly improved specific yield and reduced EPBT, the magnitude of this advantage (~3–5%) is relatively small. From a practical perspective, this suggests that altitude alone should not be considered a primary criterion for PV system site selection in regions with moderate elevation variation. Factors such as land availability, accessibility, installation conditions, grid connectivity, and system losses are likely to have a more significant impact on overall system performance and feasibility.

The findings highlight the importance of adopting a multi-criteria approach for decentralized energy planning in mountainous regions. While altitude-related climatic conditions can provide incremental performance benefits, these gains should be evaluated alongside economic, logistical, and operational considerations to ensure optimal deployment decisions.

CONCLUSION

This study evaluated the influence of altitude-associated climatic variations on photovoltaic (PV) system performance and Energy Payback Time (EPBT) across selected locations in Una district, Himachal Pradesh, using a controlled simulation framework. By maintaining identical system configuration and varying only site-specific climatic inputs, the analysis isolated the effect of altitude-linked environmental conditions on PV performance.

The results indicate a measurable but limited improvement in PV performance with increasing altitude. Specific yield increased by approximately 4%, while EPBT decreased by about 4–5% across the studied altitude range. Exploratory correlation and regression analyses further indicated a positive statistical association between altitude and specific yield, although the observed relationship remains localized to the study area and should not be generalized beyond the analysed elevation range. These variations are primarily attributed to reduced ambient temperatures at higher elevations, which improve module efficiency, while changes in solar irradiance remain comparatively small. From the perspective of sustainable rural energy planning, the findings suggest that altitude alone is not a dominant factor in determining PV system performance or lifecycle sustainability within moderate elevation ranges. Although higher-altitude locations offer slight performance advantages, their impact is incremental and should be considered alongside more influential factors such as system design, installation conditions, accessibility, and infrastructure availability.

The study contributes a district-level, controlled assessment linking altitude to EPBT, providing practical insights for decentralized energy deployment in mountainous regions. However, the analysis is based on simulation-derived climatic data and assumes uniform system configuration and embodied energy across locations. Factors such as dust accumulation, shading, degradation, and site-specific installation constraints were not explicitly considered and may influence real-world performance.

Overall, the results emphasize that while altitude-related climatic effects can enhance PV performance, their influence is modest, reinforcing the need for integrated and context-specific decision-making in rural renewable energy planning.

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