

Research paper

Quantifying Solar Irradiation and Photovoltaic Energy Yield at Optimal Tilt Angles: A Case Study of Gojra, Punjab, Pakistan

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Abstract: A high-resolution, satellite-derived solar resource assessment was conducted for Gojra, Punjab, Pakistan (31.15° N, 72.69° E) using the 2025 Global Solar Atlas (GSA, Solargis/World Bank) site report and map layers. Long-term climatological irradiance indicators-global horizontal irradiation (GHI), direct normal irradiation (DNI), diffuse horizontal irradiation (DIF), and global tilted irradiation (GTI)-were extracted and analysed at annual, monthly, and hourly time scales. The fixed-tilt design orientation was selected using the atlas-provided optimum tilt and azimuth (OPTA), and the corresponding PV electricity output (PVOU) was used to estimate the energy yield of a representative 1 MWp grid-connected PV plant under realistic loss assumptions. Gojra exhibits a strong solar resource, with annual averages of GHI $\approx 1794 \text{ kWh m}^{-2}$, DNI $\approx 1307 \text{ kWh m}^{-2}$, and GTI at OPTA $\approx 1975 \text{ kWh m}^{-2}$, yielding an expected annual generation of $\approx 1.545 \text{ GWh}$ (specific yield $\approx 1545 \text{ kWh kWp}^{-1}$; capacity factor $\approx 17.6\%$). Seasonal and diurnal profiles indicate peak generation during late spring and early summer, with thermal conditions remaining within typical operating envelopes. The resulting data-driven workflow supports evidence-based solar siting and preliminary plant design for central Pakistan.

Keyword: Solar irradiation assessment; Photovoltaic energy yield; Optimal tilt angle; Global Solar Atlas (Solargis); Gojra; Punjab; Pakistan.

1. Introduction

Solar photovoltaic (PV) technology has emerged as a central pillar of power-sector decarbonization, with global installed capacity expanding rapidly over the last decade as module costs have fallen, balance-of-system performance has improved, and policy incentives have matured across many markets [1-3]. Because PV electricity output is governed primarily by site-specific solar resource and operating temperature, credible project development still depends on localized quantification of irradiance and realistic yield estimation, even in a world of generally declining technology costs [2, 4].

In this broader context, Pakistan continues to experience structural power-sector challenges, including generation shortfalls, over-reliance on imported fossil fuels, and elevated end-user tariffs. The country is situated in a favorable solar belt, and multiple assessments now point to large technical potential for utility-scale and distributed PV deployment [5, 6]. However, converting this national-scale potential into implementable projects requires evidence at the scales at which decisions are actually made-districts, feeders, and specific sites-together with design-relevant parameters such as optimum tilt angles, expected specific yield, and capacity factor.

Mid-Punjab is particularly important in this regard. It combines strong solar resource, significant agricultural and urban demand centers, and growing pressure to reduce dependence on imported fuels, yet many of its secondary cities remain weakly characterized in terms of high-resolution irradiance climatologies and fixed-tilt optimization. Existing Pakistan-wide and South Asia-wide studies often focus on large metropolitan centers or aggregate provincial averages [7, 8], which may not adequately represent micro-climatic and land-use variability at locations such as Gojra. As a result, preliminary PV siting and sizing decisions for these districts are frequently based on generic rules of thumb rather than location-specific benchmarks.

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Gojra, located in the Faisalabad Division of central Punjab, is representative of such mid-Punjab conditions. The area exhibits a semi-arid climate with hot summers and mild winters and lies in a corridor where both utility-scale ground-mounted plants and distributed rooftop PV are technically feasible. Yet, despite its strategic location, there is a lack of published, district-level analyses that jointly report long-term irradiation components, optimum fixed-tilt geometry, and PV performance indicators at multiple time scales. This gap constrains evidence-based planning for utilities, regulators, and private developers who increasingly require bankable yield estimates and standardized performance metrics to evaluate prospective sites [5, 6].

High-resolution, satellite-derived solar resource products, such as the Global Solar Atlas (GSA) produced by Solargis for the World Bank, now offer an opportunity to address these data gaps consistently. The GSA provides long-term climatologies of global horizontal irradiation (GHI), direct normal irradiation (DNI), diffuse horizontal irradiation (DIF), global tilted irradiation (GTI), and photovoltaic power potential (PVOUT), together with optimum tilt and azimuth (OPTA) for fixed-tilt configurations. When coupled with a representative PV system configuration and realistic loss assumptions, these atlas variables can be translated into quantitative yield benchmarks for specific locations, even in the absence of dense ground-measurement networks [8- 10].

The present study applies this atlas-based approach to Gojra, central Punjab, to generate a coherent resource-to-yield assessment. Long-term annual, monthly, and hourly indicators of GHI, DNI, DIF, and GTI at the atlas-recommended OPTA are extracted, and the corresponding PVOUT is used to estimate the annual energy yield, specific yield, and capacity factor of a representative 1 MWp grid-connected PV plant under realistic loss assumptions. Seasonal and diurnal patterns in irradiation and PV output are analyzed to evaluate how the local resource interacts with fixed-tilt geometry and thermal conditions, and to infer implications for plant design and grid integration.

The aim of this study is to quantify the solar irradiation climate and fixed-tilt PV energy yield of Gojra using the 2025 Global Solar Atlas dataset and to derive location-specific performance benchmarks for a 1 MWp PV system at the optimum atlas tilt and azimuth.

The novelty of the work lies in:

- Providing a district-level PV yield benchmark for an under-studied mid-Punjab city
- Explicitly coupling atlas-based climatic indicators with geometrical optimization and PV performance metrics
- Demonstrating a transferable, data-driven workflow that can be rapidly applied to other mid-Punjab districts for preliminary solar site screening and fixed-tilt system design.

2. Literature Review

2.1 Global Trends in Solar Resource Assessment

Recent advances in remote sensing, atmospheric modelling, and radiative transfer have enabled solar resource assessments at high spatial and temporal resolution. Global and regional atlases integrate satellite observations with validated physical models to provide long-term climatologies of irradiance components and PV power potential. These products have become standard inputs for early-stage feasibility screening, particularly in regions where dense ground-measurement networks are unavailable [7, 11].

Globally, multi-source gridded solar irradiance products (satellite-based and reanalysis) are increasingly employed as the primary tool for resource assessment and preliminary site evaluation, particularly in regions with sparse ground-based measurement infrastructure. Comprehensive inter-comparison studies and worldwide validation exercises (e.g., against high-quality benchmark stations) have become progressively more robust, offering clearer recommendations on dataset selection, anticipated uncertainty margins, and climate- or location-specific error characteristics [9].

Another emerging direction is moving away from single-product validation to multi-product intercomparison, in which multiple satellite and reanalysis datasets are evaluated jointly. So that uncertainty and robustness can be rated in different timescales (hourly to annual). Comparative analyses on products such as CERES, SARA / CAMS and ERA5 / MERRA-2 consistently

show that performance is regime-dependent and varies with cloud conditions, aerosol loading, terrain complexity, and local calibration / ground truth availability. As a result, the "best" dataset is not universal but application- and context-specific [9, 12].

Along with this, the field has moved toward physically based, internally consistent retrieval frameworks that distinguish between:

- i. Clear-sky irradiance, driven primarily by aerosols, water vapor, and ozone (and related atmospheric/surface terms)
- ii. Cloud radiative attenuation, captured through cloud-index or cloud-property retrievals.

Methodological syntheses and best-practice discussions in atmospheric remote sensing increasingly frame satellite surface solar irradiance (SSI) retrieval as a coupled pipeline: satellite radiances → cloud/aerosol characterization → radiative transfer (or fast emulation) → clear-sky and all-sky SSI components (e.g., direct/diffuse/global) with uncertainty estimates [13].

A further global development is the increasing emphasis on independently validated reference products for long-term climatologies and financing-grade resource assessment workflows. Independent evaluations of widely used datasets-e.g., CERES SYN1deg (Edition 4A) surface solar radiation-provide evidence for their suitability in long-term assessment, while also quantifying uncertainty characteristics and documenting regional performance differences that are critical for risk analysis and bankability studies [10, 14].

Another unseen shift is toward a new generation of geostationary platforms with higher spatial and temporal resolution along with enabling a more nuanced representation of cloud evolution and mesoscale variability, processes that can introduce systematic bias in coarser products. Work using sensors such as China's FY-4 AGRI highlights the trajectory toward sub-kilometer native sampling (or retrieval grids) and shows that increased spatial detail can materially improve representativeness over complex terrain and in coastal cloud regimes, yielding practical gains in performance rather than purely cosmetic improvements [15].

At the same time, many regions are developing national or regional solar radiation datasets that integrate satellite retrievals, quality-controlled ground observations, and physical/statistical modeling to address local sampling gaps.

These initiatives typically aim to:

- i. Extend temporal coverage beyond sparse station records
- ii. Produce gridded datasets suitable for PV potential mapping and planning at policy-relevant scales, as illustrated by national-scale dataset construction and PV potential assessment studies [16].

A closely related phenomenon is the growing development of observation-based gridded irradiance climatologies. These are primarily derived from ground measurement networks, with spatial infilling achieved through carefully designed interpolation schemes and cloud-transmittance (or clearness-index) modeling. Such products complement satellite and reanalysis datasets and are increasingly used for benchmarking, bias diagnosis, and hybrid estimation-particularly in regions where station density is sufficient to constrain spatial gradients and heterogeneity [17].

Methodologically, the 2020-2026 literature illustrates rapid increase in machine-learning and hybrid physical-ML approaches for mapping and forecasting irradiance from satellite inputs. Rather than replacing typical physics, the more robust strategies typically use ML to emulate computationally expensive radiative transfer, correct systematic biases, or fuse satellite imagery with auxiliary atmospheric variables, often improving retrieval and forecast skill. Importantly, many of these designs preserve operational scalability for near-real-time production [18, 19].

2.2 Techniques for Solar Irradiation and Tilt Optimization

Fixed-tilt optimization is commonly addressed by selecting module orientation and inclination that maximize annual incident irradiance on the array plane. Approaches range from analytical latitude-based heuristics to numerical optimization using hourly

irradiance decomposition and transposition models. In practice, optimum tilt depends on the local balance of direct and diffuse irradiance, seasonal cloudiness, and operational constraints, so location-specific optimization is preferred over universal rules of thumb [20 – 27].

Fixed-tilt optimization for photovoltaic (PV) arrays is increasingly treated as a site-specific, model-based design problem in which tilt (β) and azimuth (γ) are selected to maximize long-term plane-of-array (POA) irradiance or energy yield while satisfying structural limits, setbacks, and shading constraints. Global analyses indicate that latitude-based rules remain useful for initial screening, but optimal angles vary with diffuse fraction, surface albedo, and seasonal cloudiness; accordingly, global optimum-tilt models that incorporate climatological drivers provide improved performance in data-sparse regions where local measurements are unavailable [28]. Annual optimum-tilt formulations have been extended to worldwide conditions and validated using meteorological datasets, enabling consistent cross-climate comparisons and supporting robust early-stage design [29].

In built environments, roof geometry and urban constraints often enforce non-ideal orientations; recent work therefore derives systematic loss functions that quantify energy penalties associated with deviations in β and γ and supports layout optimization on irregular flat roofs, including cloudy-sky regimes [30]. At plant scale, tilt interacts with row spacing and inverter sizing, and emerging evidence suggests that these coupled choices can influence PV power-forecast skill and operational decision quality-motivating joint optimization rather than tilt selection in isolation [31]. In high-latitude cold regions, snow processes and low-sun geometries further condition optimal configurations; data-driven models trained on long-term weather records (including snowfall and melt) have been proposed to reduce systematic overestimation of winter yield and improve locally optimal angle estimates [32]. For bifacial utility plants, optimal β becomes a coupled function of front- and rear-side irradiance, ground reflectance, and inter-row shading; large-area studies across Europe using typical meteorological years show that optimal tilt shifts with latitude and design parameters, and iterative searches can identify configurations that maximize bifacial energy capture [33].

Across all optimization approaches, performance depends critically on the irradiance decomposition and transposition models used to convert horizontal irradiance into POA components. Recent benchmarking studies quantify how clear-sky assumptions and transposition choices affect vertical and near-vertical planes (relevant for façade-integrated PV), improving confidence in model selection for atypical tilts [34]. More comprehensive evaluations of model chains combining multiple decomposition–transposition pairs show substantial variability in predicted POA irradiance for building-integrated PV, highlighting the need to propagate model-form uncertainty into optimization outcomes, especially under complex shading [35]. Complementary work on reverse transposition from measured global tilted irradiance improves quality control of tilted sensors and inference of horizontal components, strengthening calibration and subsequent tilt optimization at sites where only tilted measurements are available [36].

Methodologically, short-horizon reorientation strategies (e.g., periodic manual adjustments) are increasingly formulated as constrained optimization problems that trade incremental energy gains against actuation frequency by determining when and how often β should be updated [27]. Machine-learning approaches are also being used to predict optimal tilt from high-dimensional climate descriptors at large spatial scales, providing computationally efficient surrogates for repeated POA simulations and enabling rapid sensitivity analysis for planning and techno-economic studies [37]. Overall, multi-year validation against ground data remains essential for bankable tilt decisions.

2.3 Solar Potential in South Asia and Pakistan

Multiple studies have reported high solar potential across Pakistan based on satellite-derived irradiation and techno-economic evaluations, supporting the feasibility of large-scale PV integration. However, national-level assessments often require downscaling to district-relevant design parameters and performance indicators to inform project development, grid planning, and policy implementation [5, 6].

South Asia has globally competitive solar resources, and rapidly improving geospatial evidence is increasingly translating irradiation into bankable photovoltaic (PV) opportunity. Pakistan is frequently identified as a high-potential sub-region because

large parts of the Indus plains and adjacent arid and semi-arid belts combine favorable climatology, extensive developable land, and growing electricity demand. However, the 2020–2026 literature converges on a key methodological point: national mean resource values are not decision-useful for project development. Instead, solar potential must be resolved at district- and feeder-relevant scales across design variables such as GHI/DNI/GTI climatologies, variability and uncertainty, curtailment exposure, and land/rooftop availability-requiring validated radiation datasets together with explicit spatial constraints. A notable technical development in Pakistan is the systematic evaluation of reanalysis and analysis solar-radiation products against in-country measurements to quantify bias structures that would otherwise propagate into PV yield and LCOE estimates. For example, assessments in Sindh show that dataset choice and bias correction can materially affect long-term GHI representativeness and can alter the ranking of candidate zones, particularly across differing aerosol and cloud regimes [8]. At the same time, techno-economic studies are increasingly integrating satellite –and reanalysis-based irradiation with simulation platforms (e.g. SAM, PVsyst, and HOMER-class workflows), and with consistent cost-of-capital and financing assumptions So that we can go beyond the "resource potential" to the "deployable potential".

Realized system value is dominated by load coincidence along with rooftop constraints, especially where the shift is evidenced in the building-scale pathways (e.g., campus or institutional PV). The move from coarse potential maps toward implementable generation estimates conditioned on demand profiles along with physical hosting capacity is illustrated by recent work on the PV utilizability for university buildings in the Pakistan [38]. At the utility scale, concentrated solar power (CSP) along with hybrid portfolios are encompassed by Pakistan-focused assessments beyond PV, where corridors where high resource quality along with infrastructure accessibility co-exist are identified using satellite-based DNI and geospatial screening, which is followed by techno-economic feasibility testing as well as barrier diagnosis [39]. The economic viability of grid-connected PV-powered EV charging in major urban demand centers is jointly shaped by spatial heterogeneity in irradiation, local tariff structures, and utilization rates, as highlighted by studies in Multan, Lahore, and Islamabad [40].

Urban solar assessment in Pakistan has also matured beyond generic roof-area heuristics toward remote-sensing-driven inventories. Evidence from Islamabad suggests that city-scale PV opportunity can be quantified by detecting installed arrays, mapping suitable rooftops using open satellite imagery, and translating these into generation and emissions impacts-providing substantially greater spatial specificity than earlier national assessments [41, 42]. Complementary analyses of rooftop and floating PV indicate that non-traditional siting on buildings and inland water bodies can increase practical PV potential while reducing land-use conflict in densely settled districts [43, 44]. National planning studies increasingly embed solar deployment within broader decarbonization and energy-system pathways, highlighting that realizing welfare gains from Pakistan's solar resource requires coordinated attention to grid integration, market design, and investment risk alongside resource mapping [45]. Taken together, evidence from Pakistan and the wider Hindu Kush–Himalaya/South Asian context indicates that downscaling from national atlases to local development parameters is no longer an optional refinement, but a methodological requirement [46].

2.4 Tilt Angle and PV Yield in Punjab

In Punjab, several investigations have examined tilt optimization and PV yield for selected cities and districts. Reported optimum annual tilts are generally close to the local latitude, but the limited set of evaluated locations and heterogeneous methodologies constrain comparability and hinder generalization to the full province. A consistent, district-scale assessment framework remains necessary to support standardized planning across mid-Punjab [1, 3].

Published analyses in Punjab (Pakistan) commonly report annual fixed-tilt photovoltaic (PV) optima (β^*) that are close to local latitude, but the province-wide evidence base remains fragmented and therefore difficult to generalize for planning.

Non-comparability arises because studies differ in:

- i. Radiation inputs (ground measurements, satellite products, or reanalysis)
- ii. Decomposition–transposition model chains used to convert global horizontal irradiance (GHI) into plane-of-array (POA) irradiance,
- iii. Temporal basis (typical meteorological years versus multi-year time series),

- iv. Whether operational losses (e.g., soiling, mismatch, clipping, and shading) are represented in yield calculations.

Recent global tilt-modeling literature increasingly treats β^* not only as a function of latitude, but also as a function of diffuse fraction and surface albedo. This shifts optimal tilt away from a strict “latitude rule” in climates where cloud regime and aerosol loading materially modify the balance of direct and diffuse irradiance [28, 29]. This dependency is practically consequential for Punjab’s plains and peri-urban corridors because seasonal haze and winter fog episodes increase the diffuse component and reduce direct irradiance, often flattening the yield–tilt response and reducing sensitivity to small changes in β . Under these conditions, city-level rules of thumb cannot be generalized without consistent POA modeling and multi-year validation. Evidence from multi-city studies in Pakistan (including major load centers in Punjab) supports the view that seasonal tilt schedules can yield measurable gains relative to a single fixed annual tilt, but the magnitude of these gains remains contingent on the assumed radiation database and the transposition framework used to compute POA irradiance and energy yield [47].

In parallel, urban deployment in dense built environments along the Lahore–Faisalabad–Gujranwala corridor is frequently constrained by non-ideal azimuth and tilt due to roof geometry, setbacks, and inter-row shading. In such settings, “non-ideal” orientations are better treated as constrained optimization problems with explicit loss functions and roof-layout constraints, providing a methodological template for PV-dense districts in mid-Punjab where rooftop systems dominate new interconnections [30]. For utility-scale plants in southern and central Punjab, tilt selection is also increasingly understood to interact with plant design variables that influence operational performance evaluation and forecasting (e.g., inverter sizing and row spacing). Consequently, optimization based solely on irradiance maximization can be sub-optimal when integrated system-performance metrics are the objective [31].

A central methodological reason for divergence across Punjab-focused studies is the use of different decomposition–transposition chains. Recent benchmarking work in venues such as Energy and Buildings and Solar Energy indicates that model-chain selection can produce substantial spreads in estimated irradiance on tilted planes—especially for vertical or near-vertical surfaces—and can amplify uncertainty under complex sky conditions [34, 35]. These effects directly influence β^* estimation and can change yield rankings between districts, particularly where the diffuse fraction varies strongly by season. Complementary research further emphasizes that rigorous quality control of inverse (“reverse”) transposition and tilted irradiance measurements can improve the robustness of site assessments where only tilted sensors are available, which is common in operational monitoring deployments. Standardized reverse-transposition workflows therefore offer a practical pathway to district-scale calibration and intercomparison in Punjab [36].

Beyond single-angle optima, recent optimization research shows that limited reorientation strategies (e.g., two to four manual tilt adjustments per year) can be formulated as constrained optimization problems that manage the trade-off between incremental energy gains and operational complexity. This provides a structured basis for Punjab-specific seasonal strategies in contexts where manual adjustment is feasible, such as institutional or agricultural users [27]. Recent evidence in Renewable Energy examining combinations of physical models within PV performance chains (including separation, decomposition, and transposition) indicates that upstream model uncertainty propagates into downstream yield estimates [48]. Taken together, these findings motivate the establishment of a consistent, province-wide framework for Punjab that standardizes radiation inputs, model-chain choices, and validation protocols before “latitude-like” tilt conclusions are adopted as planning guidance for mid-Punjab.

2.5 Identified Research Gaps

Overall, the literature indicates that district-level irradiation and yield benchmarks are sparse for many mid-Punjab locations, and that tilt-angle optimization is frequently reported for a small subset of cities. The present study addresses this gap for Gojra by applying a unified, atlas-based workflow that reports irradiation components, optimum fixed-tilt geometry, and PV performance metrics at multiple time scales.

3. Methods

3.1 Study Area Description

Gojra (31.15° N, 72.69° E; elevation 173 m) lies in the central Punjab plain and exhibits a semi-arid climate characterized by hot summers and mild winters. The study location is shown in Figure 1, and key geographic attributes are listed in Table 1. The site is representative of mid-Punjab conditions and is therefore suitable for evaluating both utility-scale and distributed PV potential [1, 5, 49 – 50].

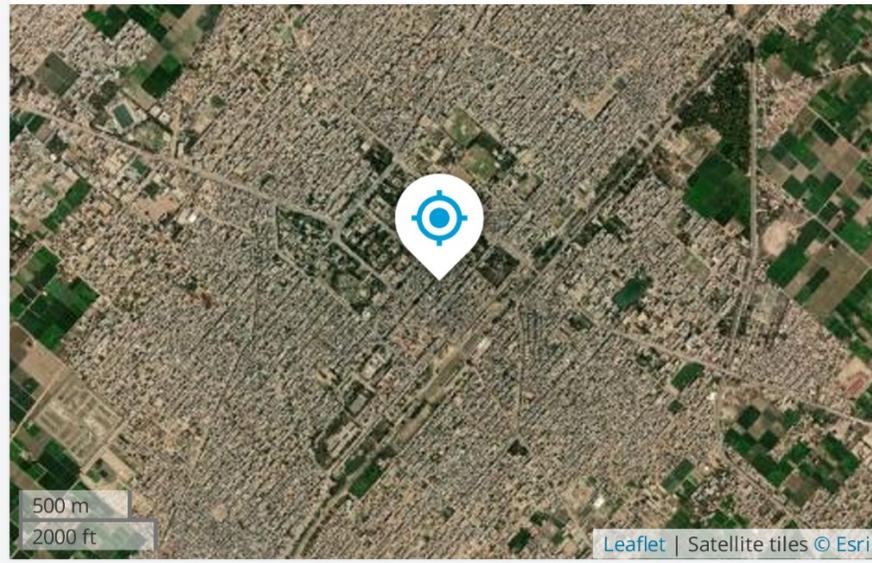


Figure 1. Satellite map showing the study location of Gojra, Punjab, Pakistan (31.15° N, 72.69° E)

To contextualize fixed-tilt orientation assumptions, the GSA horizon and sun-path diagram was examined to characterize seasonal solar elevation and azimuth trajectories (Figure 2). This analysis supports a south-facing array orientation (azimuth $\approx 180^{\circ}$) and aids interpretation of seasonal variations in irradiance and PV output.

Table 1. Site Information

Location	Faisalabad Division, Gojra Tehsil, Gojra 38100, Pakistan
Geographical coordinates	31.148237° , 72.685908° ($31^{\circ}08'54''$, $072^{\circ}41'09''$)
Time zone	UTC+05, Asia/Karachi [PKT]
Elevation	173 m

- OPTA – Optimum Tilt and Azimuth of PV Modules (°)
- PVOUT – Specific and total photovoltaic power output (kWh/kWp, GWh/year)

Annual map values and the corresponding monthly and hourly profiles were compiled into Tables 2 and 3-5. Internal consistency checks were performed by comparing annual totals against the sum of monthly values, and unit/symbol formatting was harmonized to match journal conventions.

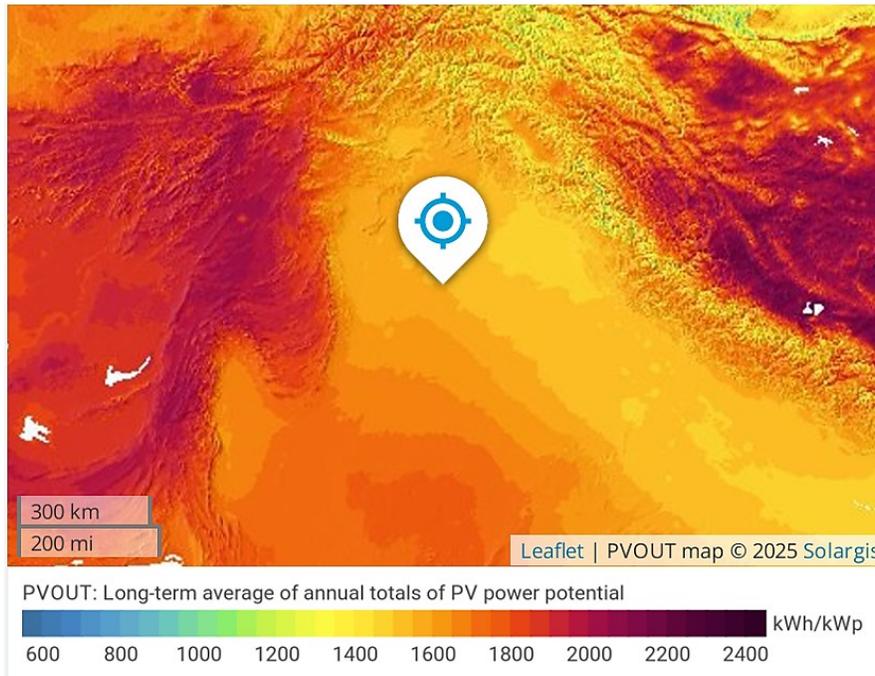


Figure 3. PVOUT map showing the long-term average of annual photovoltaic power potential across Pakistan, highlighting the Gojra site.

Table 2. Map data per Year of Gojra

Direct normal irradiation	DNI	1306.7	kWh/m ²
Global horizontal irradiation	GHI	1794.2	kWh/m ²
Diffuse horizontal irradiation	DIF	924.20	kWh/m ²
Global tilted irradiation at optimum angle	GTI_opta	1974.9	kWh/m ²
Air temperature	TEMP	24.90	°C
Optimum tilt of PV modules	OPTA	28	°
Terrain elevation	ELE	173	m

3.3 PV System Configuration

A reference 1 MWp (1000 kWp) ground-mounted, grid-connected PV system was defined to translate resource indicators into expected energy yield. The array was modelled as fixed-tilt at the GSA optimum geometry (OPTA: 28° tilt, 180° azimuth). Aggregate system losses of approximately 14% were assumed to represent inverter and wiring losses, mismatch, soiling, and temperature-related derating, consistent with typical utility-scale design practice.

3.4 Methodological Framework for Solar Energy Potential Assessment

The study followed a reproducible workflow (Figure 4). First, the site location, elevation, and climatic context were defined and supported with maps and sun-path information (Figures 1–2; Table 1). Second, the GSA–Solargis (2025) site report and map layers were retrieved and the relevant irradiance and PV potential variables were extracted (Figure 3; Table 2). Third, the fixed-tilt design orientation was selected using OPTA (tilt and azimuth that maximize annual GTI), and the associated GTI at OPTA was recorded. Fourth, a reference 1 MWp PV plant was specified and loss assumptions were applied to represent AC delivery. Fifth, PV performance indicators were computed from PVOUT, including annual energy (GWh), specific yield (kWh kWp⁻¹), and capacity factor, and monthly/hourly profiles were analysed to quantify seasonal and diurnal variability (Tables 3–5; Figures 5–7). Finally, the results were interpreted in the context of local solar planning, highlighting implications for preliminary site screening and fixed-tilt system design.

$$\text{Specific Yield } (Y_f) = \frac{\text{Annual PV Energy Output (kWh)}}{\text{Installed Capacity (kWp)}} \quad (1)$$

$$\text{Capacity Factor (CF)} = \left(\frac{\text{Annual Energy Output}}{[\text{Installed Capacity} \times 8760 \text{ h}]} \right) \times 100 \quad (2)$$

$$\text{Solar – to – Electric Conversion Efficiency } (\eta) = \frac{\text{PVOUT}}{\text{GTI}} \times 100 \quad (3)$$

Monthly and hourly profiles of irradiation and PVOUT were analysed to quantify seasonal and diurnal variability, respectively. Relationships between GTI and PVOUT were evaluated to assess the extent to which incident plane-of-array irradiance explains the simulated energy yield, and to identify periods where temperature and other loss mechanisms may modulate output [1 – 3]. Figure 4 presents the end-to-end methodological framework, linking site characterization and atlas-based data extraction to tilt optimization, PV system definition, performance indicator computation, and interpretation for district-scale solar planning.

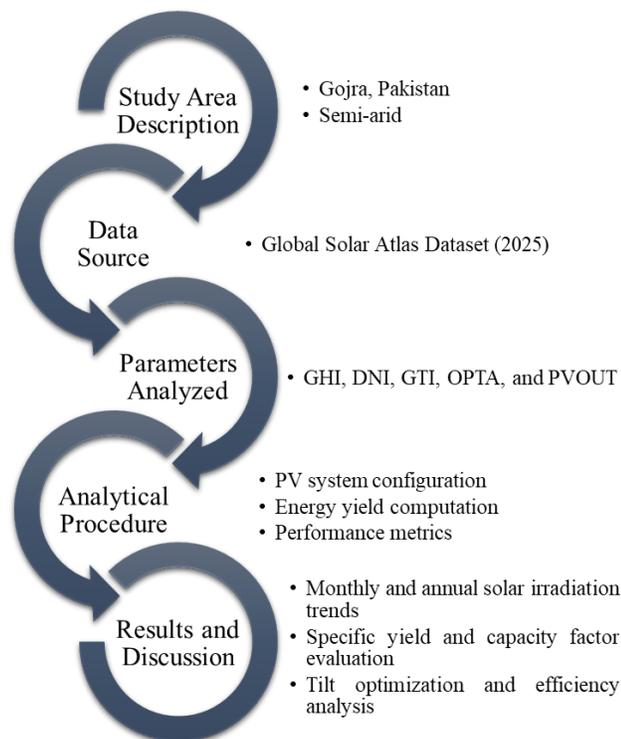


Figure 4. Methodological Framework for Solar Energy Potential Assessment

4. Results and Discussion

4.1 Annual Solar Irradiation and Fixed-Tilt Potential

The GSA dataset confirms that Gojra benefits from a strong and relatively stable solar resource. On an annual basis, GHI is approximately 1794 kWh m^{-2} , while GTI at the optimum tilt ($\text{OPTA} = 28^\circ$) reaches about 1975 kWh m^{-2} , implying an $\approx 10\%$ gain in annual incident irradiation on the tilted plane relative to the horizontal plane. Annual DNI is about 1307 kWh m^{-2} , and the long-term average air temperature is 24.9°C (Table 2), indicating a warm but not extreme thermal environment for standard PV modules.

For the reference 1 MWp fixed-tilt PV system, the atlas-based PVOUT corresponds to an annual AC energy yield of ≈ 1.545 GWh, which translates into a specific yield of $\approx 1545 \text{ kWh kWp}^{-1} \text{ year}^{-1}$ and a capacity factor of $\approx 17.6\%$. If the GTI at OPTA is interpreted as a reference yield of $\approx 1975 \text{ kWh kWp}^{-1} \text{ year}^{-1}$, the implied performance ratio (PR) is on the order of 0.78, which falls within the range typically reported for well-designed grid-connected plants in high-irradiance regions [1, 11]. Both the specific yield and capacity factor are comparable to those reported for other strong solar sites in Punjab and broader South Asia under similar modelling assumptions, suggesting that Gojra is representative of high-quality fixed-tilt PV locations in central Pakistan [5, 7, 38].

Table 3. Monthly Averages

Months	PVOUT_specific (kWh/kWp)	PVOUT_total (kWh)	DNI (kWh/m ²)
January	97.8	97,776.8	80.5
February	117.5	117,508.9	104
March	148	148,031.8	133.9
April	151.4	151,400.2	145.7
May	150.4	150,363.9	139.4
June	133.5	133,458.8	106.6
July	122.3	122,275.3	78.8
August	130.7	130,674.3	91
September	138	137,982.9	117.3
October	137.6	137,553.0	120.3
November	108.9	108,944.4	93.5
December	109.5	109,462.3	100.5
Yearly	1545.4	1545432.7	1311.7

4.2 Monthly and Seasonal Variations and DNI–GHI Behaviour

Figure 5 and Table 4 summarize the monthly evolution of PVOUT and irradiation components. PV electricity output increases from winter to late spring, peaks during April–May, and declines mildly through the hot summer months before being further reduced during the monsoon-influenced period. The seasonal cycle is clearly seen in DNI, which exhibits stronger month-to-month variability than GHI. This pattern is consistent with increased cloudiness and atmospheric moisture during the monsoon season, which reduces the direct beam component while maintaining a relatively elevated diffuse component.

The differing behaviour of DNI and GHI has practical implications for technology choice. Fixed-tilt PV systems primarily depend on GTI, which is derived from both direct and diffuse components; as a result, the seasonal modulation of PVOUT is smoother than that of DNI. By contrast, CSP and high-concentration PV systems that rely almost entirely on DNI would experience a more

pronounced seasonal fluctuation in potential output, especially during the monsoon and hazy winter months (Azhar et al., 2020; Rasheed et al., 2020). For single-axis tracking PV configurations, the higher DNI fractions in the pre-monsoon season suggest a larger relative gain from tracking at those times, whereas during highly diffuse conditions the incremental benefit of tracking would be reduced and may not justify the additional structural and operational complexity [21, 24].

From a planning perspective, the seasonal profiles imply that fixed-tilt PV in Gojra will contribute most strongly to supply during late spring and early summer, when both GTI and PVOUT are near their maxima and ambient temperatures remain within typical design envelopes. During the monsoon-affected months, the reduced DNI and moderately lower GTI imply smaller PV contributions, which should be considered in resource adequacy and storage-sizing studies for mid-Punjab grids.

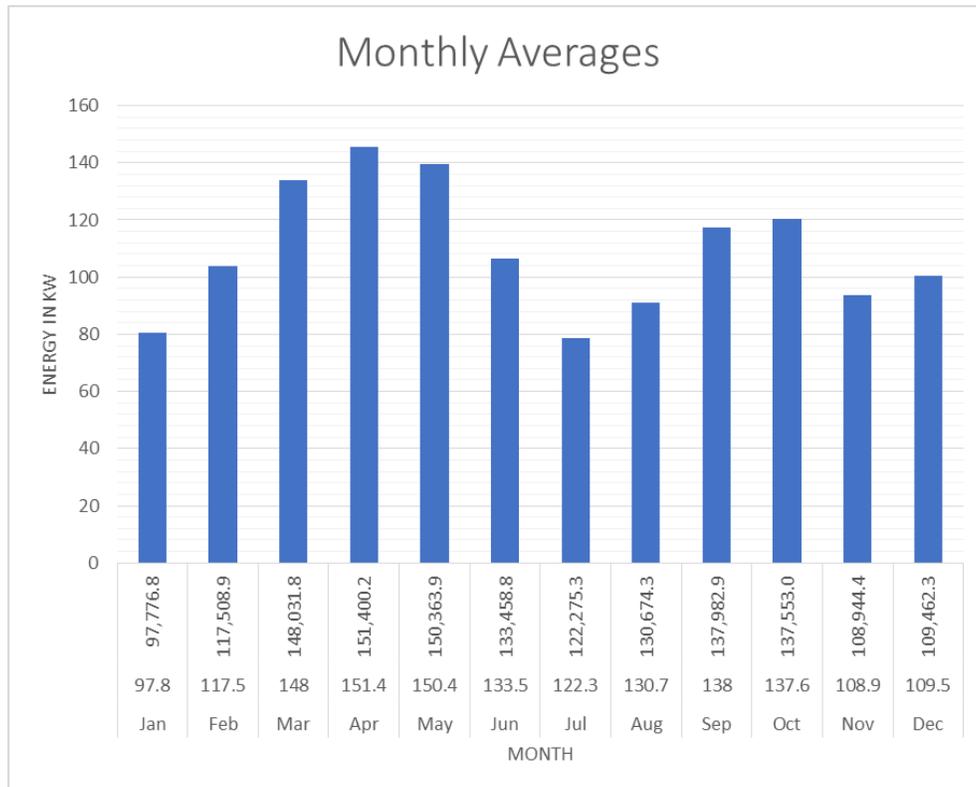


Figure 5. Monthly averages of PV electricity output (PVOUT) and solar irradiation components for Gojra (monthly profile).

4.3 Diurnal Profiles and Temperature-Related Effects

Figure 6 and Table 4 present the average hourly profiles of PVOUT, while the corresponding hourly variation of direct normal irradiation (DNI) is summarized in Table 5 and illustrated in Figure 7. The diurnal pattern is strongly peaked around solar noon, as expected for fixed-tilt south-facing arrays, but the hourly shapes vary modestly across months. In the pre-monsoon months (March–May), PVOUT rises rapidly after sunrise, maintains an extended midday plateau, and declines gradually in the late afternoon, which reflects both favorable sun-path geometry and relatively clear skies. During the monsoon and hazy winter periods, the midday plateau becomes narrower and more rounded, mirroring the higher diffuse fractions and increased cloud variability.

Deviations from a strictly proportional relationship between GTI and PVOUT across months can be interpreted in terms of temperature-related efficiency losses and seasonal changes in diffuse fraction. Although only annual average air temperature is available from the atlas, it is reasonable to expect that module cell temperatures in Gojra exceed 45–50 °C during hot, low-wind afternoons in May–June, which would temporarily reduce efficiency relative to cooler seasons. This effect helps explain why the monthly PVOUT in the hottest months does not increase in direct proportion to GTI and why specific yield per unit GTI can be

marginally lower than in cooler months, even though irradiance remains high. The implied annual PR of ≈ 0.78 suggests that aggregate losses-including temperature, soiling, wiring, mismatch, and inverter conversion-are consistent with typical utility-scale PV systems in comparable climates [1, 11].

Table 4. Total photovoltaic power output [Wh]

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	0	0	0	0	0	0	0	0
5 - 6	0	0	0	848	6576	7218	1964	104	0	0	0	0
6 - 7	0	132	6602	45808	73085	66207	46420	40668	27850	10943	152	0
7 - 8	20100	53659	120828	189407	204391	173232	142096	154294	175494	158726	83638	32916
8 - 9	167771	235813	304729	365075	360740	308474	266415	300051	346538	348446	269424	227831
9 - 10	301736	404372	473276	516605	497000	439438	386132	436371	497968	505372	421283	384735
10 - 11	400551	534487	596441	626557	592575	537502	477948	533749	603976	606411	528482	497451
11 - 12	476636	621502	674060	685735	640860	587271	534559	582703	653199	662333	581365	565593
12 - 13	510008	650546	694580	694012	642092	593667	540731	577719	645895	661616	574094	579116
13 - 14	484780	616542	666196	641214	600181	558794	500684	530781	590509	592352	506633	525014
14 - 15	407665	511981	551498	546281	512623	476827	421699	443972	486647	465476	390916	416621
15 - 16	281148	366153	404387	408051	383149	361197	320071	328167	347918	303983	231834	259847
16 - 17	103231	184471	234875	242838	232983	224994	201552	201591	189261	117640	43661	41921
17 - 18	466	17088	47747	81372	94052	100236	92515	79264	34177	3895	0	0
18 - 19	0	0	0	2869	10143	13570	11578	5866	0	0	0	0
19 - 20	0	0	0	0	0	0	0	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0
Sum	3154092	4196746	4775219	5046672	4850450	4448627	3944364	4215300	4599432	4437193	3631482	3531045

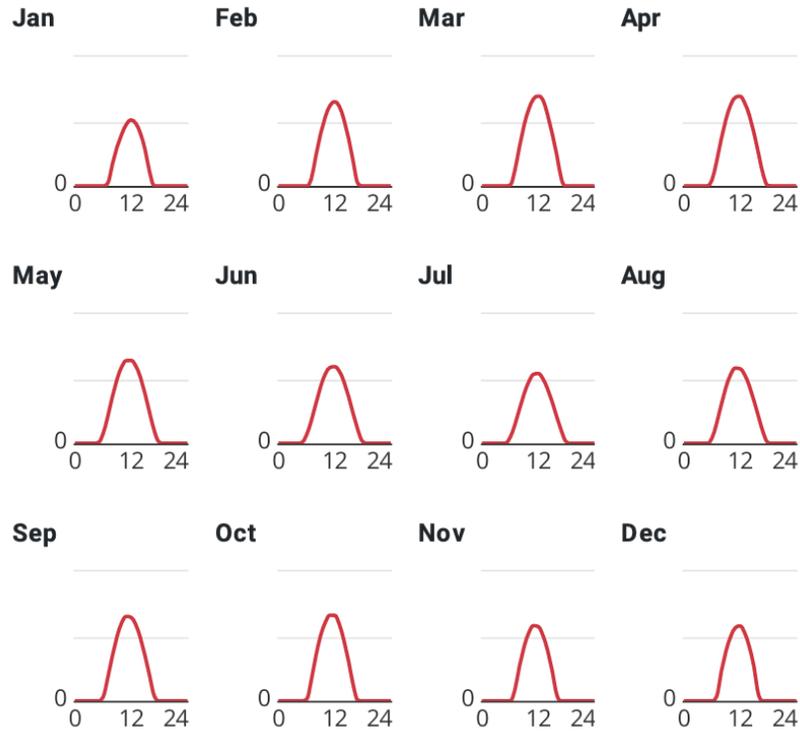


Figure 6. Average hourly profiles of PV electricity output (PVOUT) and solar irradiation components for Gojra (diurnal profile)

Table 5. Direct normal irradiation [Wh/m²]

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	0	0	0	0	0	0	0	0
5 - 6	0	0	0	0	5	5	0	0	0	0	0	0
6 - 7	0	0	8	77	101	69	32	35	31	13	0	0
7 - 8	24	72	164	246	232	158	102	131	200	183	97	49
8 - 9	165	260	316	380	350	257	188	234	327	332	265	249
9 - 10	253	366	430	479	442	344	253	316	421	432	358	356
10 - 11	310	448	502	549	500	399	295	366	489	496	427	428
11 - 12	361	499	545	584	527	423	320	381	509	528	458	476
12 - 13	386	517	566	592	529	429	320	370	497	530	454	488
13 - 14	374	504	557	558	513	420	304	337	461	490	416	459

14 - 15	337	444	480	504	467	382	267	292	398	412	347	396
15 - 16	270	358	394	421	384	314	220	234	320	311	247	289
16 - 17	117	225	287	312	278	220	153	163	215	147	49	50
17 - 18	0	22	70	150	154	120	80	74	43	5	0	0
18 - 19	0	0	0	4	15	14	9	3	0	0	0	0
19 - 20	0	0	0	0	0	0	0	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0
Sum	2597	3715	4319	4856	4497	3554	2543	2936	3911	3879	3118	3240

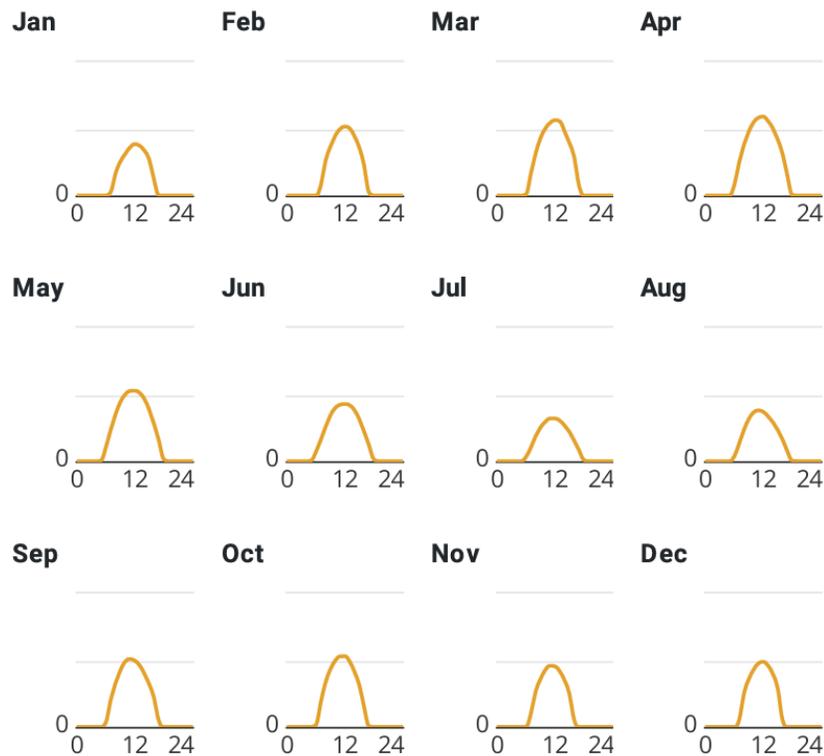


Figure 7. Average hourly profile of direct normal irradiation (DNI) for Gojra.

4.4 PV Yield, Capacity Factor, and Significance of Tilt Optimization

The atlas-derived annual energy yield of ≈ 1.545 GWh for a 1 MWp system, together with a capacity factor of $\approx 17.6\%$, places Gojra in the upper segment of performance ranges reported for fixed-tilt PV in Punjab and neighboring regions [5, 7, 38]. If the same system were deployed on a horizontal plane, the $\approx 10\text{--}12\%$ reduction in GTI relative to the OPTA configuration would translate directly into a similar reduction in annual energy yield, reducing specific yield to roughly $1370\text{--}1400$ kWh kWp⁻¹ year⁻¹.

In absolute terms, this corresponds to a loss of about 150–180 MWh year⁻¹ for a 1 MWp plant, which is non-trivial in both technical and financial terms.

From a practical perspective, the tilt-induced energy gain is significant for multiple stakeholders. For utility-scale projects, the additional 10–12 % energy can improve project economics by increasing revenue and lowering the levelized cost of electricity (LCOE), especially when feed-in tariffs or avoided generation costs are substantial. For commercial, industrial, or institutional consumers adopting rooftop or ground-mounted PV, the same gain directly reduces net electricity purchases from the grid and can shorten payback periods, provided that structural and land-use constraints allow the use of tilt-optimized mounting systems [38, 40]. Given that tilt optimization is a one-time design decision with negligible operating overhead, the results for Gojra strongly support adoption of atlas-informed optimal tilts rather than defaulting to horizontal or purely latitude-based heuristics.

4.5 Broader Planning Implications for Mid-Punjab

The analysis demonstrates that GSA-based indicators can provide a coherent resource-to-yield workflow for district-scale planning in mid-Punjab. By supplying internally consistent climatologies of GHI, DNI, DIF, GTI, optimum tilt geometry, and PVOUT, the atlas allows planners and developers to rapidly derive specific yield and capacity factor benchmarks for candidate sites, even where ground-based measurement networks are sparse [8 – 10]. For Gojra, the resulting metrics—GTI at OPTA of ≈ 1975 kWh m⁻² year⁻¹, specific yield of ≈ 1545 kWh kWp⁻¹ year⁻¹, and capacity factor of ≈ 17.6 %—place the location firmly in the category of high-quality PV sites within Pakistan.

At the same time, the seasonal and diurnal profiles derived here help inform broader system planning questions that go beyond single-point yield estimates. The timing of peak PV output relative to local load profiles, the reduced output during monsoon-affected months, and the moderate but non-negligible temperature-related losses all have implications for grid integration, storage sizing, and hybridization with other resources [43, 44]. For example, the concentration of PV output in late spring and early summer may align well with agricultural water-pumping demand, while the mid-day peaks in PVOUT suggest that battery storage or demand-side management could be used to mitigate ramping and curtailment risks in distribution feeders with high PV penetration [39, 40]. Because the workflow used here is explicitly reproducible, it can be extended to other mid-Punjab districts to support comparative site ranking and integrated energy-system planning [46, 51 – 52].

4.6 Uncertainty and Atlas-Based Data Considerations

The results presented in this study are derived entirely from atlas-based, satellite-driven solar resource data, and therefore inherit the strengths and limitations of such products. Global validation exercises indicate that modern satellite and reanalysis irradiance datasets typically achieve annual-mean GHI biases within a few percent at well-instrumented locations, but errors can be larger in regions with complex cloud regimes, aerosol variability, or sparse ground-truth data [8 – 10]. In Pakistan, recent evaluations have shown that dataset choice and bias-correction strategies can materially affect long-term GHI estimates and, in turn, PV yield and LCOE calculations [8, 53].

For Gojra, this implies that the reported GTI, PVOUT, and derived metrics (specific yield, capacity factor, implied PR) should be interpreted as best-estimate benchmarks rather than exact predictions. Uncertainty in annual GHI on the order of ± 5 –10 % would translate into comparable uncertainty in annual energy yield and financial indicators, which is important for investors and lenders considering project bankability. As recommended in the Future Work section, establishing a calibrated ground-measurement station and conducting at least 12 months of co-located atlas–measurement comparison would enable quantification and, if necessary, correction of any systematic biases at Gojra [13, 17]. Nevertheless, in the pre-measurement phase, the GSA-based workflow presented here provides a well-founded starting point for screening and preliminary design of PV projects in mid-Punjab.

5. Conclusions

Using the 2025 Global Solar Atlas (GSA–Solargis) dataset, this study quantified the solar resource and fixed-tilt PV yield potential of Gojra, central Punjab. The site exhibits high long-term irradiation, with GTI at the optimum fixed tilt (28°) of 1974.9 kWh m⁻² year⁻¹ and a simulated PV output of approximately 1.545 GWh year⁻¹ for a 1 MWp grid-connected system. The

corresponding specific yield ($\approx 1545 \text{ kWh kWp}^{-1} \text{ year}^{-1}$) and capacity factor ($\approx 17.6\%$) indicate strong suitability for PV deployment. Adopting the OPTA-based tilt increases expected energy capture by approximately 10–12% relative to a horizontal configuration, underscoring the value of geometry-informed design. Overall, the reported benchmarks provide a defensible basis for preliminary site screening and early-stage system sizing for mid-Punjab.

Future work should move beyond atlas-based screening toward measurement-validated, deployment-ready planning. Priority directions include:

1. Establishing ground validation by installing a calibrated pyranometer and meteorological station in Gojra and quantifying GSA bias/uncertainty over ≥ 12 months
2. Evaluating alternative orientation strategies by simulating annual fixed tilt, seasonal adjustment schedules, and single-axis tracking to quantify incremental energy gains (%) and cost-benefit trade-offs
3. Refining loss modelling through temperature and soiling sensitivity analyses using measured module temperature and local aerosol/dust indicators, with reporting of performance ratio (PR) and uncertainty bounds
4. Assessing grid-integration impacts and storage requirements using the hourly PVOUT profile to quantify ramp rates, curtailment risk, and optimal battery capacity under specified reliability targets
5. Extending the framework across mid-Punjab using GIS constraints (land use, protected areas, grid proximity, and exclusion zones) to produce a ranked suitability map for utility-scale PV development.

Conflict of Interest

The author declares no conflict of interest related to the publication of this research.

Declaration of Generative AI

ChatGPT (OpenAI) was used to assist with language editing and formatting. The author reviewed and revised all AI-assisted text and takes full responsibility for the final manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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