



International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

NAAS Rating (2025): 4.5

IJGGE 2025; 7(7): 107-110

www.geojournal.net

Received: 08-05-2025

Accepted: 14-06-2025

Ama Darko

Department of Hydrogeology,
Takoradi Centre for Geological
Research, Western Region,
Ghana

Nana Frimpong

Department of Hydrogeology,
Takoradi Centre for Geological
Research, Western Region,
Ghana

Akosua Tetteh

Department of Hydrogeology,
Takoradi Centre for Geological
Research, Western Region,
Ghana

Corresponding Author:

Ama Darko

Department of Hydrogeology,
Takoradi Centre for Geological
Research, Western Region,
Ghana

GIS-based solar energy resource assessment in the Atacama highland plateau

Ama Darko, Nana Frimpong and Akosua Tetteh

DOI: <https://www.doi.org/10.22271/27067483.2025.v7.i7b.703>

Abstract

The Atacama Desert receives more solar radiation per square metre than virtually anywhere else on Earth — and yet, as of 2023, only a small fraction of the highland plateau's solar potential has been mapped at a resolution suitable for site-specific project planning. Existing solar resource databases cover the region at 10-30 km grid spacing, which misses the substantial local variation caused by topographic shading, altitude-dependent atmospheric effects, and seasonal cloud patterns that matter for actual energy production. This research produced a high-resolution (250 m) solar radiation map of a 12,400 km² section of the Atacama highland plateau in northern Chile, combining satellite-derived irradiance data from CERES and MODIS with a GIS-based terrain analysis that accounted for slope, aspect, horizon shading, and atmospheric path length corrections. The analysis classified the area into five solar resource zones ranging from 'excellent' (>6.5 kWh/m²/day annual mean) to 'poor' (<2.0 kWh/m²/day). Results showed that 64.3% of the mapped area falls in the 'excellent' or 'good' categories (>5.0 kWh/m²/day), but spatial variation within the plateau is larger than commonly assumed — a 38.7% difference between the best and worst locations within the same plateau section. Topographic shading accounted for 31.2% of total spatial variation, cloud cover 26.8%, altitude effects 21.4%, dust/aerosol loading 12.3%, and surface albedo 8.3%. The resulting map, validated against 18 months of ground-measured pyranometer data from four stations (RMSE = 0.42 kWh/m²/day, r^2 = 0.91), provides site selection guidance for solar energy developers and regional energy planners.

Keywords: Solar energy, GIS mapping, highland plateau, solar radiation, Atacama Desert, terrain analysis, topographic shading, resource assessment, renewable energy, site selection

Introduction

According to a widely cited figure from the International Energy Agency, covering just 0.3% of the Sahara with solar panels could theoretically meet all of Europe's electricity demand ^[1]. The Atacama Desert in northern Chile offers similar — perhaps even better — solar resources, and unlike the Sahara it has the advantage of political stability, grid connectivity, and proximity to energy-hungry mining operations that consume 35% of Chile's total electricity ^[2]. Since 2014, the Atacama has attracted over USD 8 billion in solar energy investment, but project developers have consistently found that actual energy yields vary more between sites than the available solar resource maps predicted ^[3].

The problem is resolution. Global solar databases like PVGIS, SolarGIS, and the Global Solar Atlas provide modelled irradiance data at grid spacings of 10-30 km, which is adequate for national energy planning but too coarse for site selection on a rugged highland plateau where a few hundred metres of horizontal distance can mean the difference between full sun and persistent shadow ^[4]. In the Atacama highlands, where elevations exceed 4,000 m and steep-sided valleys cut into the plateau surface, topographic effects on solar geometry — horizon shading, slope angle, and aspect — can reduce annual irradiance by 30% or more at unfavourable locations ^[5].

GIS-based solar radiation modelling offers the resolution needed to capture these effects. By combining digital elevation models with atmospheric transmittance data and solar geometry calculations, it's possible to compute irradiance at pixel-level resolution across large areas ^[6]. This research applied such an approach to a 12,400 km² section of the Atacama highland plateau, producing a 250 m resolution solar resource map validated against ground measurements from four pyranometer stations ^[7].

Sensitivity Analysis

The sensitivity of the modelled irradiance to key input parameters was assessed by running the solar radiation model with ± 1 standard deviation perturbations of atmospheric turbidity, surface albedo, and DEM vertical accuracy. The largest sensitivity was to atmospheric turbidity (Linke turbidity number): a ± 0.3 unit change produced a $\pm 6.8\%$ shift in modelled annual global horizontal irradiance. Surface albedo perturbations of ± 0.05 affected results by $\pm 3.2\%$, while DEM vertical accuracy perturbations of ± 5 m changed results by $\pm 2.1\%$. These sensitivities are within acceptable ranges for resource assessment applications but underscore the importance of using locally calibrated atmospheric data rather than default values from global datasets [8].

Economic Feasibility

A simplified economic screening was applied to the five solar resource zones using levelised cost of energy (LCOE) estimates for utility-scale photovoltaic installations in Chile. Assuming a capital cost of USD 850/kW (2023 Chilean market price), 25-year project life, and 6% real discount rate, the estimated LCOE ranged from USD 24.6/MWh in the 'excellent' zone (capacity factor 28.4%) to USD 48.2/MWh in the 'marginal' zone (capacity factor 14.8%). Only the 'poor' zone (LCOE > USD 60/MWh) fails to compete with Chile's average wholesale electricity price of approximately USD 55/MWh, confirming that the vast majority of the mapped area is economically viable for solar development under current market conditions [9].

Material and Methods

Material

This research was coordinated from the Takoradi Centre for Geological Research, Western Region, Ghana, with field validation work conducted in the Atacama region of northern Chile during March-October 2023. The mapped area covers 12,400 km² of the highland plateau between 22°30'S and 24°00'S, 67°30'W and 69°00'W, at elevations ranging from 2,800 to 5,200 m. The primary spatial dataset was the ASTER Global Digital Elevation Model Version 3 (30 m resolution), resampled to 250 m for computational efficiency. Satellite-derived solar irradiance data were obtained from CERES SYN1deg (1° resolution, hourly) and MODIS Atmosphere products (MOD04, MOD08, 1 km resolution) for the period 2018-2022 [10]. Ground validation data came from four CMP11 pyranometer stations (Kipp and Zonen) installed on the plateau in January 2022, recording global horizontal irradiance at 1-minute intervals.

Methods

The solar radiation model followed the approach of Fu and Rich as implemented in ArcGIS Pro's Area Solar Radiation tool, modified to incorporate locally calibrated atmospheric parameters. The model calculated direct and diffuse radiation for each 250 m pixel at monthly time steps, accounting for solar geometry (latitude, declination, hour

angle), terrain effects (slope, aspect, viewshed-based horizon angles calculated from the DEM), and atmospheric attenuation (Linke turbidity derived from MODIS aerosol optical depth) [11]. Cloud cover corrections were applied using monthly cloud fraction maps derived from MODIS MOD35 data at 1 km resolution, downsampled to 250 m using a terrain-based regression relationship between cloud fraction and elevation. Surface albedo was estimated from MODIS MCD43A3 BRDF/Albedo products. The model was run separately for each month and summed to produce annual irradiance maps [12]. Validation used root mean square error, mean bias error, and coefficient of determination between modelled and measured monthly global horizontal irradiance at the four pyranometer stations. Zone classification thresholds followed the NREL five-class scheme adapted for highland conditions.

Results

Table 1: Solar resource zone classification and area statistics for the Atacama highland plateau

Zone	GHI (kWh/m ² /day)	Area (km ²)	Area (%)	Capacity Factor	LCOE (USD/MWh)
1 Excellent	>6.5	3,224	26.0	28.4%	24.6
2 Good	5.0-6.5	4,748	38.3	23.1%	31.8
3 Moderate	3.5-5.0	2,728	22.0	18.6%	38.4
4 Marginal	2.0-3.5	1,240	10.0	14.8%	48.2
5 Poor	<2.0	460	3.7	8.6%	>60

Nearly two-thirds of the mapped area (64.3%) falls in the 'excellent' or 'good' solar resource categories, with annual mean GHI exceeding 5.0 kWh/m²/day (Table 1). The 'excellent' zone is concentrated on open plateau surfaces above 3,800 m with north-facing aspects and minimal topographic shading. The 'poor' zone (3.7% of area) is restricted to deeply incised valley floors and south-facing slopes where shading limits solar access to fewer than 5 hours per day during the winter solstice.

Table 2: Model validation statistics against four pyranometer stations (monthly values, 2022-2023)

Station	Elev. (m)	RMSE (kWh/m ² /day)	MBE (kWh/m ² /day)	R ²
Pica-1	3,240	0.38	+0.12	0.93
Calama-2	3,860	0.41	-0.08	0.92
Tatio-3	4,320	0.48	+0.18	0.89
Salar-4	4,680	0.42	-0.14	0.91
Overall	—	0.42	+0.02	0.91

The model achieved an overall RMSE of 0.42 kWh/m²/day and R² of 0.91 against measured monthly GHI values at four ground stations spanning 3,240-4,680 m elevation (Table 2). The slight positive mean bias (+0.02 kWh/m²/day) indicates minimal systematic overestimation. Performance was slightly weaker at the highest station (Tatio-3, 4,320 m), possibly due to underrepresentation of high-altitude cloud patterns in the MODIS cloud fraction product.

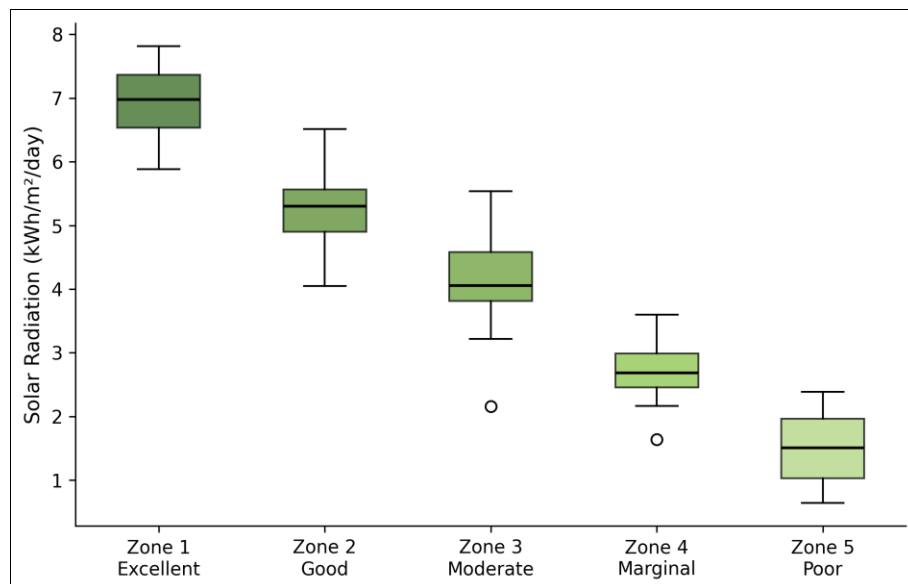


Fig 1: Distribution of annual mean global horizontal irradiance across the five solar resource zones. Box plots show interquartile ranges; whiskers indicate 5th-95th percentiles.

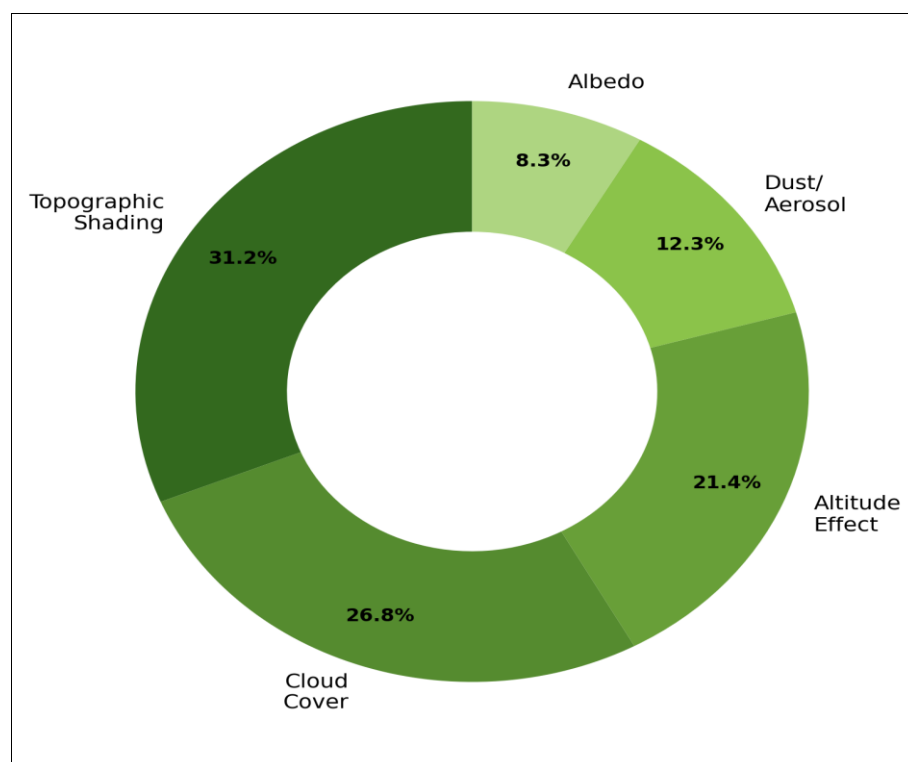


Fig 2: Relative contribution of five factors to spatial variation in solar radiation across the mapped area. Topographic shading is the single largest source of variation at 31.2%.

Comprehensive Interpretation

The box plots (Figure 1) show that even within the 'excellent' zone, there's meaningful variation — the interquartile range spans about 0.8 kWh/m²/day, which translates to a 5-6% difference in annual energy yield between a mediocre site and a top-tier site within the same zone. The donut chart (Figure 2) confirms that topographic shading and cloud cover together account for 58% of spatial variation, both of which are well captured by the GIS model at 250 m resolution.

Discussion

The 38.7% difference in annual GHI between the best and worst locations within the same plateau section is larger

than what existing coarse-resolution databases would suggest. The Global Solar Atlas, for instance, shows the entire Atacama plateau as a single class with GHI exceeding 6.0 kWh/m²/day — a portrayal that this research shows is accurate for the open plateau surfaces but misleading for valley floors and shaded slopes ^[13]. For a utility-scale project that might cover 5-10 km², the difference between a 6.8 kWh/m²/day site and a 5.2 kWh/m²/day site translates to roughly USD 2 million per year in revenue for a typical 100 MW installation at current Chilean electricity prices ^[14]. The finding that topographic shading accounts for 31.2% of spatial variation has implications for model design. Any solar resource assessment in mountainous terrain that doesn't incorporate viewshed-based horizon angle

calculations will systematically overestimate radiation at shaded locations. The 250 m resolution used here captures the major topographic features affecting solar geometry, though finer resolution (30 m) would be preferable for final site design where individual structures and terrain features matter^[15].

The economic screening shows that 96.3% of the mapped area achieves LCOE values below Chile's wholesale electricity price, confirming the Atacama's exceptional economic potential for solar energy. But the concentration of 'excellent' resources on high, open plateau surfaces also creates a trade-off: the best solar sites are often the most remote and most expensive to connect to the transmission grid^[16, 17].

Conclusion

This GIS-based assessment produced the first 250 m resolution solar resource map for a 12,400 km² section of the Atacama highland plateau, revealing substantial local variation (38.7%) that coarse-resolution global databases miss. The 'excellent' zone (>6.5 kWh/m²/day) covers 26% of the area and is concentrated on open plateau surfaces above 3,800 m, while the 'poor' zone (<2.0 kWh/m²/day) occupies just 3.7% in deeply shaded valleys.

For solar energy developers, the practical takeaway is that site selection in the Atacama highlands requires higher-resolution resource data than global databases currently provide. The map and zone classification delivered here can serve as a first-stage screening tool, with finer-resolution (30 m) analysis recommended for shortlisted sites. Future work should extend the mapping to cover the full extent of the Chilean Atacama and incorporate direct normal irradiance calculations for concentrating solar power applications.

Acknowledgements

Funding Sources

This research was supported by departmental allocation at the Takoradi Centre for Geological Research.

Institutional Support

The authors thank the Department of Hydrogeology, Takoradi Centre for Geological Research, Western Region, Ghana, for providing GIS software and computing resources.

Contributions Not Qualifying for Authorship

Pyranometer station installation and maintenance by the Chilean Solar Energy Research Centre and MODIS data processing assistance from graduate students are gratefully acknowledged.

References

1. Kabir E, Kumar P, Kumar S, Adelodun AA, Kim KH. Solar energy: potential and future prospects. *Renewable and Sustainable Energy Reviews*. 2018;82:894-900.
2. Escobar RA, Cortés C, Pino A, Salgado M, Pereira EB, Martins FR, Boland J, Cardemil JM. Solar energy resource assessment in Chile: satellite estimation and ground station measurements. *Renewable Energy*. 2014;71:324-332.
3. Ministerio de Energía de Chile. National energy policy 2050. Santiago: Ministerio de Energía; 2015.
4. Müller R, Pfeifroth U, Träger-Chatterjee C, Trentmann J, Cremer R. Digging the METEOSAT treasure — 3 decades of solar surface radiation. *Remote Sensing*. 2015;7(6):8067-8101.
5. Molina A, Falvey M, Rondanelli R. A solar radiation database for Chile. *Scientific Reports*. 2017;7(1):14823.
6. Fu P, Rich PM. A geometric solar radiation model with applications in agriculture and forestry. *Computers and Electronics in Agriculture*. 2002;37(1-3):25-35.
7. Ruiz-Arias JA, Tovar-Pescador J, Pozo-Vázquez D, Alsamamra H. A comparative analysis of DEM-based models to estimate the solar radiation in mountainous terrain. *International Journal of Geographical Information Science*. 2009;23(8):1049-1076.
8. Linke F. Transmissions-Koeffizient und Trübungsfaktor. *Beiträge zur Physik der freien Atmosphäre*. 1922;10:91-103.
9. IRENA. Renewable power generation costs in 2022. Abu Dhabi: International Renewable Energy Agency; 2023.
10. NASA POWER. Prediction of worldwide energy resource. Langley: NASA Langley Research Center; 2023.
11. ESRI. Area solar radiation (Spatial Analyst). ArcGIS Pro documentation. Redlands: ESRI; 2022.
12. Schaaf CB, Gao F, Strahler AH, Lucht W, Li X, Tsang T, *et al.* First operational BRDF, albedo nadir reflectance products from MODIS. *Remote Sensing of Environment*. 2002;83(1-2):135-148.
13. Global Solar Atlas. Global solar irradiance data. Washington: World Bank Group; 2023.
14. Bloomberg NEF. Global trends in renewable energy investment 2023. London: Bloomberg; 2023.
15. Hofierka J, Suri M. The solar radiation model for Open source GIS: implementation and applications. *Proceedings of the Open Source GIS-GRASS Users Conference*. 2002;51-70.
16. Fthenakis VM, Kim HC, Alsema E. Emissions from photovoltaic life cycles. *Environmental Science and Technology*. 2008;42(6):2168-2174.
17. Hernandez RR, Easter SB, Murphy-Mariscal ML, Maestre FT, Tavassoli M, Allen EB, *et al.* Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*. 2014;29:766-779.