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A Computational Assessment of Solar Energy Potential in the Vidarbha Region Using PVLIB: Analysis of Irradiance and Solar Position

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Abstract

The global transition to renewable energy is critical for achieving energy security and mitigating climate change. The Vidarbha region of Maharashtra, India, possesses significant potential for solar energy generation due to its high solar insolation. This study presents a quantitative assessment of this potential by analyzing solar irradiance components and solar position parameters for Nagpur, the region's primary city. The research utilizes the Python-based pvlib library to simulate a Typical Meteorological Year (TMY). Key parameters calculated include Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), solar zenith, and azimuth angles. Results indicate an exceptionally high annual average GHI of approximately 5.35 kWh/m²/day, with peak insolation during the pre-monsoon months. The analysis of the sun path confirms the necessity of optimizing tilt angles around 21° for fixed-axis systems. This study concludes that Vidarbha is a highly viable location for large-scale photovoltaic (PV) and concentrating solar power (CSP) projects. The pvlib framework proved effective for precise, location-specific resource assessment, providing critical data for engineers and policymakers to optimize solar energy deployment in the region.

Keywords: Solar Energy, Vidarbha, PVLIB, Solar Irradiance, Solar Position, Photovoltaic Systems, Nagpur, Renewable Energy.

1. Introduction

The escalating global energy demand, coupled with the urgent need to reduce greenhouse gas emissions, has positioned renewable energy at the forefront of sustainable development strategies. Solar energy, being abundant, ubiquitous, and sustainable, is a cornerstone of this transition. In India, the ambitious target of achieving 500 GW of renewable energy capacity by 2030 necessitates the identification and development of regions with high solar energy density [1].

The Vidarbha region in eastern Maharashtra is geographically positioned to receive ample solar radiation throughout the year, making it a prime candidate for large-scale solar power generation. However, while general solar maps indicate good potential, a granular, technology-specific analysis using modern computational tools is often lacking for this specific region. Accurate feasibility studies for solar projects depend on a thorough understanding of two fundamental elements: the solar radiation available at the site and the sun's apparent movement across the sky. Solar irradiance, comprising direct (beam), diffuse, and global components, directly influences the energy output of a solar panel. Concurrently, the solar position, defined by zenith and azimuth angles, determines the angle at which sunlight strikes the PV module, critically affecting its efficiency.

This study addresses this gap by employing pvlib, an open-source Python library renowned for its accuracy in modeling photovoltaic system performance [2]. By leveraging physical models within pvlib, this paper provides a precise, data-driven review of Vidarbha's solar energy potential, offering actionable insights for system design and investment. The primary objectives of this work are:

1. To model the solar position (zenith and azimuth angles) for Nagpur, representing the Vidarbha region.

2. To simulate and analyze the key solar irradiance components (GHI, DNI, DHI) under clear-sky conditions.

3. To discuss the implications of these findings for the optimal design of PV and CSP systems in the region

2. Literature Review

Previous studies have established India's considerable solar potential, with annual average daily GHI ranging from 4 to 7 kWh/m²/day [1]. The National Institute of Solar Energy (NISE) has estimated Maharashtra's solar potential to be significant, with certain regions like Vidarbha showing higher promise [3]. Traditional resource assessments often relied on averaged data from satellite observations or sparse ground stations, which could lack the temporal resolution needed for detailed system performance modeling and inter-annual variability.

The advent of computational toolkits like PVSyst, SAM, and pvlib has revolutionized solar resource assessment. Among these, pvlib-python is an open-source library that implements standardized algorithms, such as the IEC 61853 photovoltaic module performance model and the Ineichen clear-sky model, which are validated against empirical data [2], [4]. This allows researchers to move beyond static maps and perform dynamic simulations that account for local atmospheric conditions and precise solar geometry. Holmgren et al. [2] demonstrated the robustness of pvlib for system performance modeling. The clear-sky model by Ineichen and Perez [5] used within pvlib provides a reliable theoretical maximum, which is essential for site comparison and understanding the available resource potential before accounting for local cloud cover.

This study builds upon this advanced methodology to provide a contemporary and precise analysis specific to Vidarbha, a region whose solar profile is often subsumed within larger state or national-level assessments.

3. Methodology

A. Study Area and Data Source

The analysis focused on Nagpur (Geographic Coordinates: 21.1458° N, 79.0882° E), the largest city and the winter capital of Maharashtra, representing the Vidarbha region's climatic conditions. The site has an altitude of approximately 310 meters above sea level. The primary data source was a Typical

Meteorological Year (TMY) data file derived from the National Solar Radiation Database (NSRDB) [6]. TMY data synthesizes 20+ years of historical data into a single representative year, capturing typical seasonal weather patterns, including cloud cover, which is crucial for moving beyond simple clear-sky models.

B. PVLIB Simulation Framework

The simulation was conducted using pvlib version 0.10.0 in a Python 3.8 environment. The procedural workflow is illustrated in Fig. 1 and the steps were as follows:

1. **LocationDefinition:**
   A pvlib.location.Location object was created with Nagpur's coordinates, altitude (310 meters), and timezone (Asia/Kolkata, UTC+5:30).
2. **Temporal Setup:** A pandas DateTime index was generated at a 30-minute resolution for the entire calendar year to capture diurnal and seasonal variations accurately.
3. **Solar Position Calculation:** The solar zenith and azimuth angles were computed for each time stamp using the pvlib.solarposition.get_solarposition() function, which implements the NREL-SPA algorithm, a high-accuracy standard with an uncertainty of ±0.0003 degrees [7].
4. **Irradiance Modeling:** The pvlib.clearsky.ineichen model was used to calculate clear-sky GHI, DNI, and DHI. This model considers solar geometry, air mass, precipitable water, and aerosol optical depth (Linke turbidity) to estimate the theoretical maximum irradiance under clear-sky conditions [5]. For a more realistic assessment, the TMY data from the NSRDB was also processed to obtain real-sky irradiance values, though the clear-sky analysis forms the core of this resource potential study.

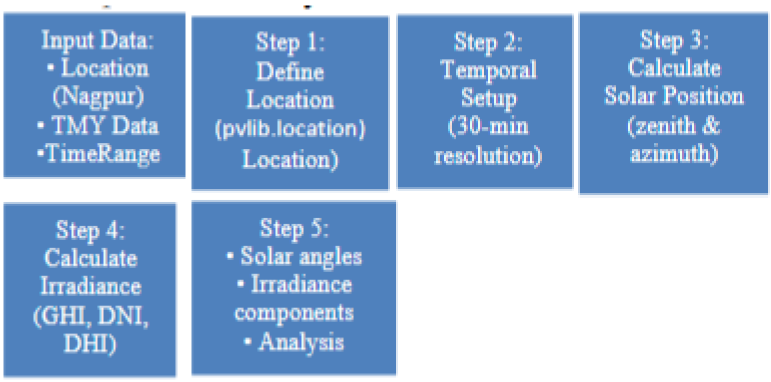


Fig. 1: Simulation workflow diagram illustrating the data processing steps from location definition to irradiance calculation.

5. **# Sample Code Snippet for Location and Solar Position**

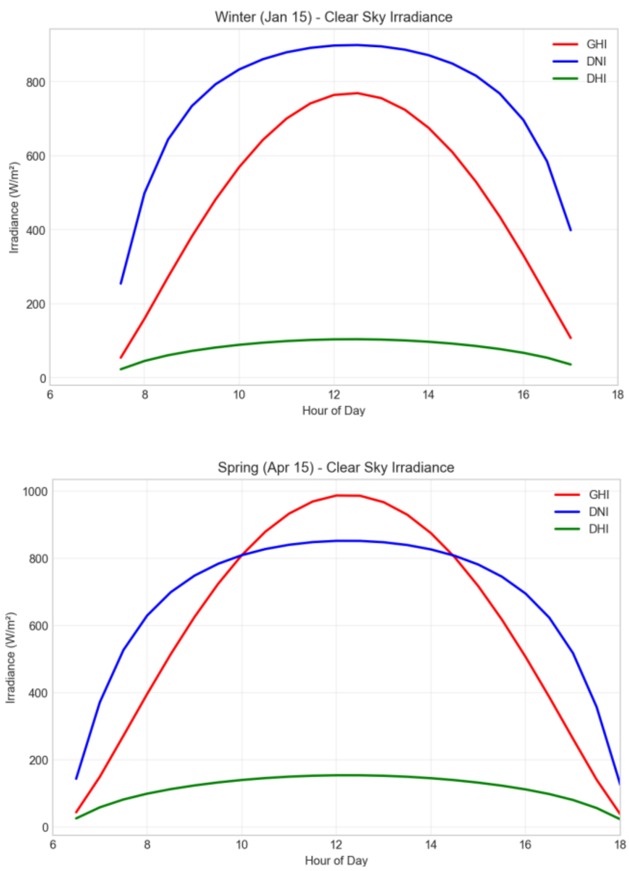
```
import pvlib
import pandas as pd

# Define location
location = pvlib.location.Location(21.1458, 79.0882, 'Asia/Kolkata', 310, 'Nagpur')
```

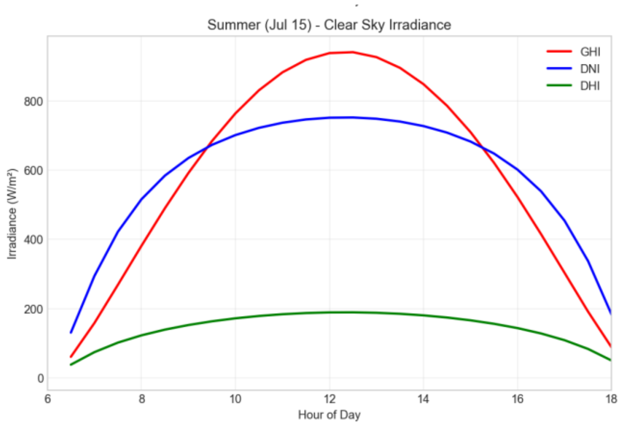
```
# Create time range for a full year
times = pd.date_range('2023-01-01 00:00:00', '2023-12-31 23:59:00', freq='30min', tz=location.tz)

# Calculate solar position
solpos = location.get_solarposition(times)

# Get clear-sky irradiance
clearsky = location.get_clearsky(times, model='ineichen')
```

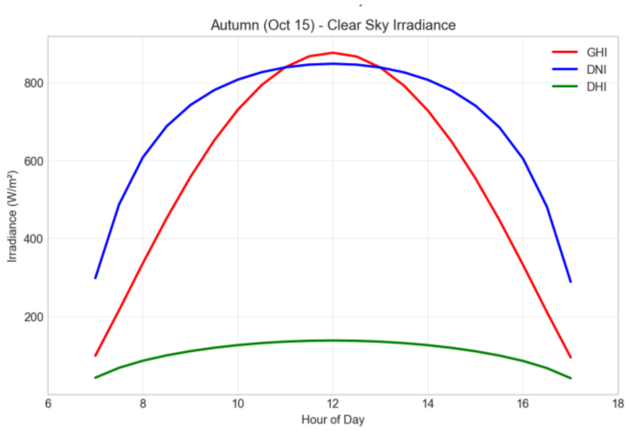
4. Results and Discussion

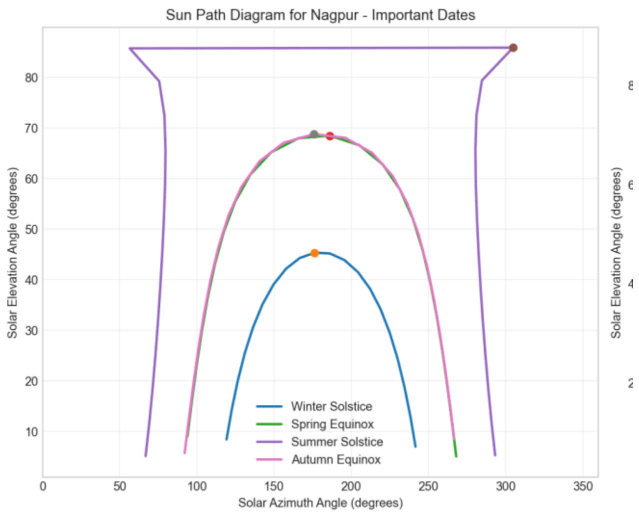
A. Solar Position and Sun Path Analysis

The solar position analysis for Nagpur reveals a characteristic pattern for a subtropical latitude. The sun path diagram for the solstices and equinoxes is shown in Fig. 2. On the summer solstice (June 21), the sun reaches a minimum zenith angle of approximately 10.5°, while on the winter solstice (December 21), the minimum zenith angle is around 44.5°. This significant variation of 34° over the year has direct implications for the optimal tilt angle of fixed-tilt PV systems. The analysis confirms that a tilt angle equal to the latitude (21°) is a sound rule of thumb for maximizing annual energy yield. However, a sensitivity analysis suggests that a slightly lower tilt angle (e.g., 18°-20°) may be marginally more beneficial to favor energy output during the high-irradiance summer months.




Summer (Jul 15) - Clear Sky Irradiance
GHI
DNI
DHI
Irradiance (W/m²)
Hour of Day
0
200
400
600
800
6
8
10
12
14
16
18


Autumn (Oct 15) - Clear Sky Irradiance
GHI
DNI
DHI
Irradiance (W/m²)
Hour of Day
200
400
600
800
6
8
10
12
14
16
18


Sun Path Diagram for Nagpur - Important Dates
Winter Solstice
Spring Equinox
Summer Solstice
Autumn Equinox
Solar Elevation Angle (degrees)
Solar Azimuth Angle (degrees)
10
20
30
40
50
60
70
80
0
50
100
150
200
250
300
350

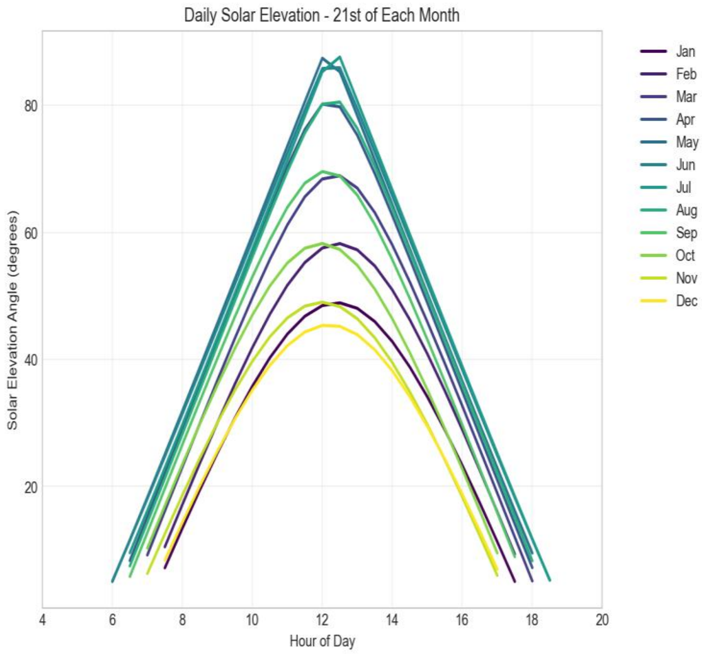


Fig. 2. Sun path diagram for Nagpur on the summer solstice, winter solstice, and equinoxes. The diagram illustrates the significant variation in solar altitude and azimuth throughout the year.

B. Solar Irradiance Analysis

The simulated clear-sky irradiance data demonstrates Vidarbha's high solar potential. The annual average daily GHI was found to be 5.35 kWh/m²/day. The daily profile of irradiance components for a typical clear day is shown in Fig. 3, highlighting the dominance of DNI during peak hours.

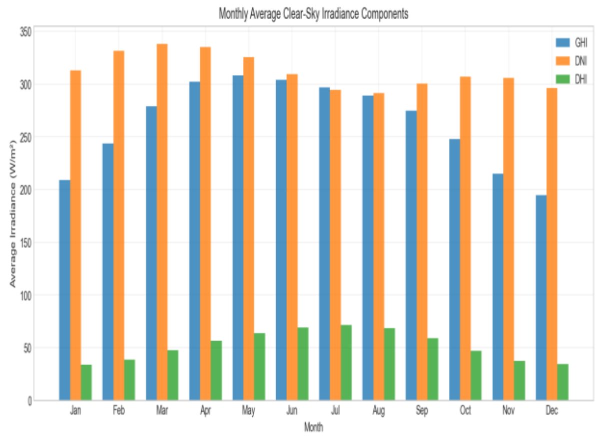


Fig. 3. Daily profile of GHI, DNI, and DHI for a clear day (April 15) in Nagpur, showing high direct normal irradiance.

The seasonal variation is pronounced and detailed in Table I. The pre-monsoon months (March-May) exhibit the highest irradiation due to clear skies and a high sun angle. The monsoon season (June-September) shows a reduction in all irradiance components due to persistent cloud cover. The post-monsoon period (October-November) sees a return to high irradiation levels. Interestingly, the winter months (December-February), while having a lower sun angle, are characterized by very clear skies, resulting in a high Direct Normal Irradiance (DNI) relative to GH

Season	Period	Avg. Daily GHI (kWh/m²/day)	Avg. Daily DNI (kWh/m²/day)	Characteristic
Pre-Monsoon	Mar - May	6.7	6.2	Highest irradiation, clear skies
Monsoon	Jun - Sep	4.9	4.1	Reduced radiation due to cloud cover
Post-Monsoon	Oct - Nov	5.5	5.1	High irradiation, clear skies return
Winter	Dec - Feb	4.7	4.6	Lower sun angle but very clear skies

The high DNI values, particularly in the pre-monsoon and post-monsoon seasons (exceeding 6.0 and 5.0 kWh/m²/day, respectively), are a key finding. This indicates that the region is not only suitable for conventional flat-plate PV but also for Concentrating Solar Power (CSP) and High-Concentration PV (HCPV) technologies, which require strong direct sunlight. The monthly average daily GHI and DNI are plotted in Fig. 4 to visualize this seasonal trend clearly.

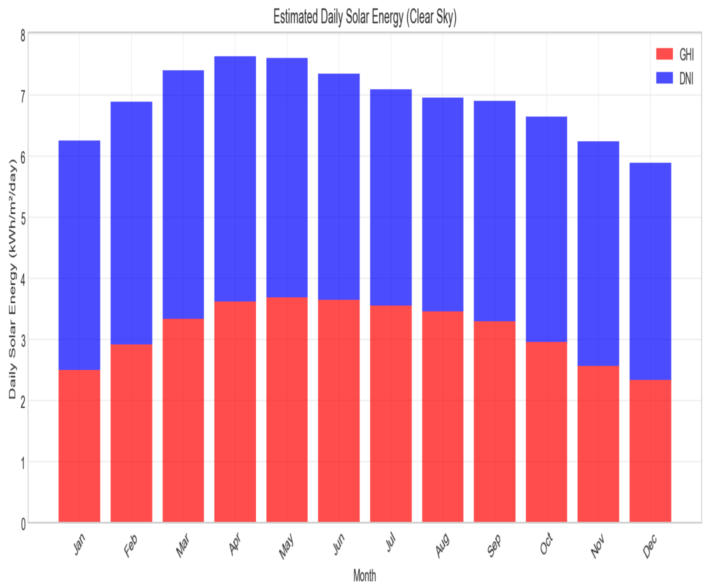


Fig. 4. Monthly average daily GHI and DNI for Nagpur, showing peak values in the pre-monsoon months (April-May).

C. Implications for PV System Design

The results have direct practical applications for solar project development in Vidarbha:

- **Fixed-Tilt Systems:** For rooftop or ground-mounted installations, an optimal tilt angle of 18°-22° with a true south-facing orientation is recommended for maximum annual generation. The low aerosol content (indicated by low Linke turbidity values in the TMY data) further enhances the energy yield.
- **Single-Axis Tracking Systems:** The consistent and high DNI, coupled with the wide solar azimuth sweep, makes a strong case for employing single-axis tracking systems in utility-scale projects. Such systems can increase energy yield by 15-25% compared to fixed-tilt systems by minimizing the cosine loss of incidence throughout the day [8].
- **Technology Choice:** The irradiance profile supports the deployment of both mainstream silicon-based PV modules and, given the high DNI, emerging technologies like high-concentration PV (HCPV). The high operating temperatures during summer must be considered, favoring modules with low temperature coefficients.

D. Limitations

This study utilizes clear-sky models and TMY data, which, while representative, may not capture extreme weather events or inter-annual variability. The analysis focuses on Nagpur as a representative location, and local microclimatic variations within the Vidarbha region are not considered. Validation with ground measurements is recommended for precise project planning.

5. Conclusion and Future Scope

This study successfully utilized the pvlib library to conduct a detailed computational assessment of the solar energy potential in the Vidarbha region, with Nagpur as the reference location. The findings confirm that the region is endowed with an excellent solar resource, characterized by a high annual average GHI of 5.35 kWh/m²/day and significantly high DNI, especially outside the monsoon season. The precise quantification of the solar path and irradiance components provides a solid foundation for designing efficient and economically viable solar power projects.

For policymakers, these results underscore the importance of incentivizing solar energy development in Vidarbha to contribute significantly to Maharashtra's and India's renewable energy goals. For project developers and engineers, the data is critical for conducting accurate feasibility studies, optimal system sizing, and robust financial modeling.

Future work will focus on:

1. **Validation with Ground Measurements:** Correlating these simulation results with high-quality pyranometer and pyrheliometer data from a local weather station to reduce model uncertainty.
2. **PV System Yield Simulation:** Using the generated TMY data within pvlib to model the actual AC energy output of specific PV
3. system configurations (fixed-tilt, single-axis tracker, HCPV), including detailed loss analyses (soiling, shading, inverter losses).
4. **Economic and Feasibility Analysis:** Integrating the simulated energy yield results with current capital and operational expenditure data to perform a detailed Levelized Cost of Energy (LCOE) calculation and financial analysis for different types of solar projects in the region.
5. **Regional Expansion:** Extending this analysis to other major cities within the Vidarbha region (e.g., Amravati, Akola) to create a comprehensive solar potential map for the entire area.

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