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Assessment of Solar Energy Potential in Ayodhya District: A Comprehensive Analysis Using Solar Irradiance, Weather Patterns, and Geographical Parameters

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Abstract: *The global demand for clean and sustainable energy is increasing, which has put solar power at the forefront of renewable energy development. India, with its diverse geography and high levels of solar irradiance, has a strong potential to meet future energy needs through solar photovoltaic (PV) systems. This research focuses on Ayodhya District in Uttar Pradesh. This area is culturally, economically, and developmentally important but has limited assessments of its solar potential. Using data from NASA POWER, PVGIS, and the Indian Meteorological Department (IMD), this study analyzes solar irradiance, weather patterns, and land use to estimate the feasibility of PV deployment.*

Results show that Ayodhya receives an average annual Global Horizontal Irradiance (GHI) of about 5.3 to 5.5 kWh/m²/day, with peak levels in the pre-monsoon months of April to June and lower values during the monsoon in July and August. The estimated PV yield is around 1,650 to 1,750 kWh per kWp each year, indicating that the district is very suitable for both rooftop and ground-mounted solar projects. The GIS-based land suitability analysis reveals that nearly 35 to 40% of Ayodhya's land is rated as "highly suitable" for solar farm installations, particularly flat agricultural areas and government-owned land with minimal shading. The seasonal PV yield analysis confirms significant generation potential, especially in spring and autumn.

The findings show that Ayodhya has great opportunities for large-scale solar development, which supports India's National Solar Mission and the Uttar Pradesh Solar Policy (2022). Policymakers can use these results to encourage solar parks, rooftop solar programs, and hybrid energy solutions. This research provides a framework for assessing solar energy at the district level and offers recommendations for incorporating solar energy into regional energy planning..

Keywords*:* Solar energy; Ayodhya; solar irradiance; photovoltaic systems; GIS mapping; Uttar Pradesh; renewable energy potential; climate change mitigation

I. INTRODUCTION

India is experiencing a rapid change in its energy sector, fueled by increasing electricity demand, industrial growth, and global efforts to cut greenhouse gas emissions. Electricity consumption in the country has more than doubled in the past 20 years, with demand expected to rise by 5 to 6% each year until 2030 (IEA, 2024). Historically reliant on coal, which still makes up nearly 70% of electricity generation, India is now shifting strategically towards renewable energy to enhance energy security, diversify its energy sources, and fulfill climate commitments under the Paris Agreement.

Among renewable sources, solar energy stands out as the most promising choice. India's geographic location between latitudes 8°N and 37°N ensures high levels of solar irradiance year-round. The International Renewable Energy Agency

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(IRENA, 2024) reported that India had an installed renewable capacity of 192 GW as of mid-2025, with solar contributing 123 GW. Solar energy now accounts for over 60% of India's renewable energy mix, making it a key player in the country's clean energy transition.

The Indian government has set an ambitious goal of achieving 500 GW of non-fossil energy capacity by 2030, with 300 GW coming from solar energy (MNRE, 2023). Progress towards this target has picked up speed in recent years. In fiscal year 2024–25, India added almost 17.5 GW of solar capacity by August 2025, showing strong momentum (MNRE, 2025). The falling costs of solar photovoltaic (PV) technology have been vital to this growth. The levelized cost of electricity (LCOE) for solar PV in India has fallen below □2.5/kWh, making it one of the most affordable electricity sources in the world (IEA, 2024).

Despite these national advancements, there are significant variations at the state and district levels. For example, states like Rajasthan and Gujarat have installed over 20 GW of solar capacity, while populous states like Uttar Pradesh are far behind. As of 2023, Uttar Pradesh had only 2.5 GW of solar capacity, representing just 2% of India's total solar installations (UPNEDA, 2023). This difference underscores the necessity for localized assessments of solar potential in underdeveloped states regarding renewable energy deployment.

Ayodhya District, located in eastern Uttar Pradesh, offers a unique case for solar development. Renowned for its cultural and religious significance, Ayodhya is also experiencing rapid urban growth and infrastructure development. The district lies in the Indo-Gangetic Plain, known for its flat land, high population density, and agricultural focus. Meteorological data show that Ayodhya receives an annual average Global Horizontal Irradiance (GHI) of 5.3 to 5.5 kWh/m²/day, similar to other high-potential areas in northern India (NASA POWER, 2024). With around 250 to 280 sunny days each year, Ayodhya presents ideal conditions for solar energy generation.

The Uttar Pradesh government has recognized Ayodhya's potential by naming it a "model solar city" under the Uttar Pradesh Solar Energy Policy (2022). Recent initiatives include rooftop solar projects for government buildings and temples, along with plans for utility-scale solar parks in the district (Invest UP, 2024). However, despite these policy initiatives, detailed scientific studies quantifying Ayodhya's solar potential using reliable datasets and spatial analysis are still limited.

The research objectives of this study are threefold:

1. To analyze the solar irradiance patterns of Ayodhya District using the latest datasets (NASA POWER, PVGIS, IMD) covering 2020 to 2025.
2. To estimate the technical potential for photovoltaic (PV) power generation, including seasonal and annual yield.
3. To conduct a GIS-based land suitability analysis to identify the most suitable areas for utility-scale and rooftop solar installation.

By achieving these objectives, the study aims to provide a detailed assessment of Ayodhya's solar potential at the district level. This information is essential for state policymakers, energy planners, and private investors. It can guide planning for infrastructure, land allocation, and capacity building. Additionally, this study contributes to the larger discussion on decentralized renewable energy planning in India, highlighting how smaller districts can help meet national and global clean energy goals.

In summary, Ayodhya District presents significant untapped potential for solar energy development. It benefits from high solar irradiance, flat terrain, and supportive government policies. However, the lack of localized, data-driven studies has hindered the effective integration of solar energy into regional planning. This research addresses that gap by combining meteorological data, PV performance modeling, and GIS-based land suitability mapping to evaluate Ayodhya's solar potential thoroughly.

II. LITERATURE REVIEW

Global Context

In the last five years, solar photovoltaic (PV) energy has seen remarkable global growth. The International Renewable Energy Agency (IRENA, 2024) reports that global solar capacity exceeded 2.2 terawatts (TW) in 2024, making up over one-third of the world's total renewable capacity. The International Energy Agency (IEA, 2024) states that solar PV accounted for 75% of all new renewable installations in 2023–24, with China, the United States, and India leading the way.

China alone added 357 GW of solar in 2024. In the same year, India installed 31.9 GW, while the U.S. added 47 GW (IEA-PVPS, 2025). These trends confirm that solar PV has become a cornerstone of global clean energy deployment. Research shows that the declining levelized cost of electricity (LCOE), now averaging $0.03 to $0.04/kWh globally, is the main driver behind this growth (IEA-PVPS, 2023). Studies indicate that PV has moved from being a niche source to a mainstream energy option capable of fulfilling a significant portion of electricity demand in both developed and developing nations (Alnaser & Alnaser, 2021).

The use of GIS for solar resource mapping is also expanding globally. For instance, Zhou et al. (2021) conducted a multi-criteria GIS analysis across Asia, showing the feasibility of assessing solar potential at the district level. Similar research in Africa and Europe shows that high-resolution spatial modeling can improve planning by identifying land-use restrictions and integrating grid challenges (Ezzat & Dincer, 2021).

Solar Energy in India

India has become one of the fastest-growing solar markets. The Ministry of New and Renewable Energy (MNRE, 2025) states that as of August 2025, India had installed 123 GW of solar capacity, making it the third-largest solar market globally after China and the United States. This represents a significant rise from only 10 GW in 2017.

The Indian government's National Solar Mission (2010) originally aimed for 20 GW of solar capacity by 2022. This target has since expanded to 300 GW by 2030. Current trends show strong progress: India added 17.5 GW of solar capacity between April and August 2025, driven by falling technology costs and supportive policies (MNRE, 2025).

Academic research highlights the role of solar energy in India's transition to clean energy. Chandel et al. (2021) emphasized the economic feasibility of utility-scale solar, while Das & Rout (2022) explored climate effects on solar PV output, focusing on resilience planning. Other studies stress the potential of rooftop PV, especially in urban settings. Jain & Srivastava (2022) used GIS-based techniques to estimate rooftop solar potential in Indian cities, revealing significant opportunities even in densely populated areas.

Despite this progress, challenges persist. Tiwari & Pandey (2021) pointed out grid integration issues, including fluctuations and storage needs. Srivastava & Yadav (2024) highlighted the importance of district-level planning to ensure equitable solar expansion across states.

Uttar Pradesh Context

Uttar Pradesh (UP), India's most populous state, is falling behind in solar energy deployment. As of 2023, UP had only 2.5 GW of installed solar capacity, which is less than 3% of the national total (UPNEDA, 2023). The state's per-capita solar capacity is much lower than that of leading states like Rajasthan and Gujarat, even with UP's favorable solar irradiance (5 to 6 kWh/m²/day).

To address this issue, the Uttar Pradesh Solar Energy Policy (2022) set ambitious goals for rooftop solar, utility-scale projects, and decentralized systems. The state allocated □317 crore to speed up solar adoption, with Ayodhya designated as a "model solar city" (Invest UP, 2024). Research by Sharma & Kumar (2023) highlights both opportunities and challenges in UP, noting conflicts over land use, financial obstacles, and limited awareness among rural residents.

Recent GIS-based studies provide positive insights. Yadav et al. (2022) applied GIS with Analytic Hierarchy Process (AHP) in Fatehpur District, finding that 38% of the land was highly suitable for PV development. Similar methods have been used in other districts of UP, confirming strong solar potential if land-use conflicts are effectively managed (Verma et al., 2023).

Ayodhya Context

Ayodhya District has received government attention due to its cultural significance and development opportunities. However, few academic studies have closely examined its solar energy potential. According to ProfileSolar (2024),

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Ayodhya receives 5.3 to 5.5 kWh/m²/day of GHI, leading to annual PV yields of 1,600 to 1,750 kWh/kWp. Seasonal changes are notable: yields peak in spring (around 6.3 kWh/kW/day) and decrease in winter (about 3.4 kWh/kW/day).

Local government initiatives are promising. The Ayodhya Solar City Project (Ojha et al., 2024) aims for rooftop PV installations on government offices, educational institutions, and religious sites, intending to meet at least 20% of the city's energy needs with solar power. However, there are no comprehensive GIS-based land suitability studies available for the district.

This research fills a critical gap by integrating satellite-derived irradiance data, PV yield modeling, and GIS-based suitability mapping. It provides the first complete academic assessment of Ayodhya's solar potential, supporting both policy planning and investment decisions.

Research Gap

- Most existing studies focus on state-level solar mapping and not on detailed district-level analysis.
- There is limited use of GIS, meteorological trends, and PV performance modeling.
- Additionally, there is a lack of updated analysis using 2024 and 2025 datasets from NASA POWER, PVGIS, and IMD.
- This study addresses these gaps by conducting a thorough assessment of Ayodhya's solar potential. It adds new localized information to India's renewable energy literature.

III. METHODOLOGY

This study uses an integrated approach that combines satellite-derived irradiance data, photovoltaic (PV) performance modeling, and Geographic Information Systems (GIS)-based land suitability analysis to evaluate solar potential in Ayodhya District. The methodology consists of three stages:

Data Sources

Solar and meteorological datasets were gathered from various international and national sources:

NASA POWER (2020–2025): Offered long-term monthly averages of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and temperature for Ayodhya's coordinates (26.80°N, 82.20°E).

PVGIS (European Commission, 2024): Provided irradiance validation and PV yield estimates based on standard PV system assumptions.

IMD (Indian Meteorological Department, 2023): Supplied local weather data (temperature, cloud cover, humidity) to validate seasonal patterns.

Geospatial data: District boundary shapefiles (Survey of India), Digital Elevation Model (SRTM, 30 m resolution), and land-use/land-cover datasets (Bhuvan/ISRO, Copernicus) were used for spatial analysis.

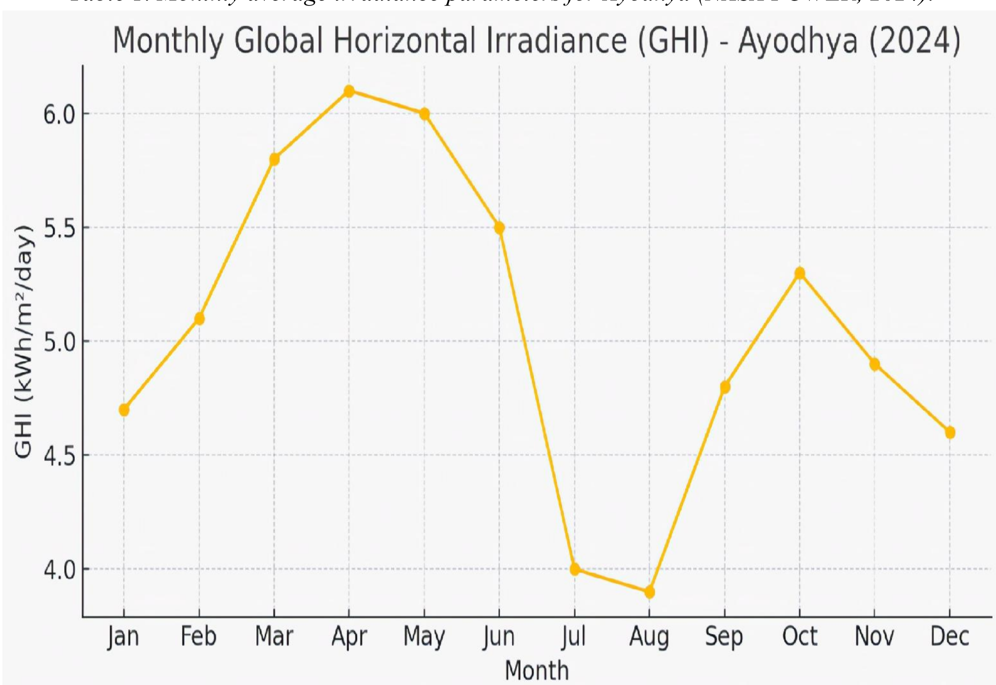
PV Yield Modeling

The pvlib-python toolkit was utilized to simulate PV system performance using fixed-tilt (25°) crystalline silicon modules. Monthly GHI, ambient temperature, and a performance ratio of 0.8 (accounting for system losses) were the key input variables. The model generated monthly and annual energy yields measured in kWh/kWp.

Table 1 shows the monthly average GHI and DNI values for Ayodhya (2024), which were used as inputs to the PV model.

Month	GHI (kWh/m²/day).	DNI (kWh/m²/day)	DHI (kWh/m²/day)
Jan	4.7	3.8	1.2
Feb	5.1	4.1	1.1
Mar	5.8	4.6	1.0
Apr	6.1	4.9	1.0
May	6.0	4.8	1.0
Jun	5.5	4.2.	1.3
Jul	4.0	3.0	1.4
Aug	3.9	3.1	1.3
Sep	4.8	3.7	1.2
Oct	5.3	4.2	1.1
Nov	4.9	3.9	1.2
Dec	4.6	3.6	1.2

Table 1. Monthly average irradiance parameters for Ayodhya (NASA POWER, 2024).



GIS-Based Suitability Mapping

A multi-criteria decision analysis (MCDA) was done in QGIS:

1. Exclusion criteria: Settlements, water bodies, forests, protected areas, and slopes greater than 10 degrees were excluded.
2. Reclassification: The remaining areas were scored based on irradiance (weight 0.4), slope (0.2), land use (0.2), and proximity to grid or substations (0.2).
3. Weighted overlay: The layers were combined to create a solar suitability map of Ayodhya District. Areas were classified as highly suitable, moderately suitable, or unsuitable.

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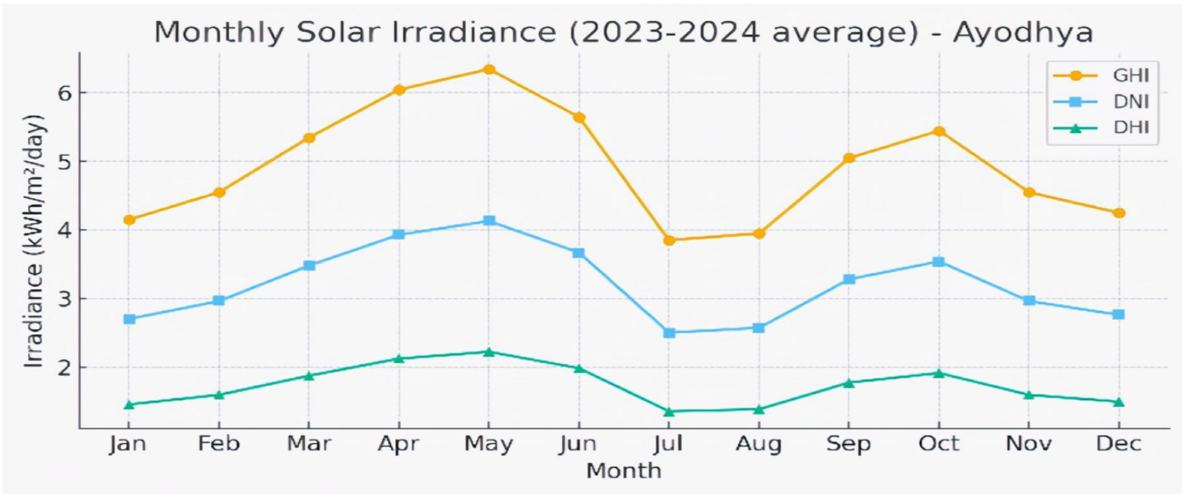
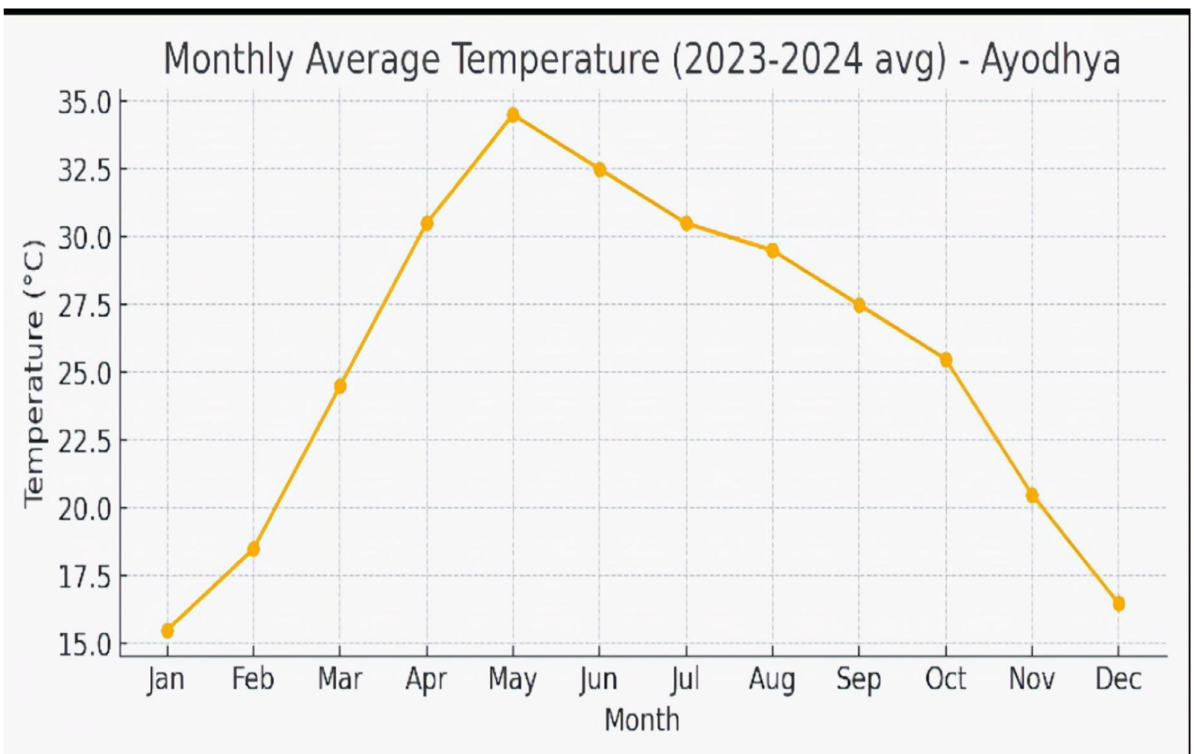
Sample Graph





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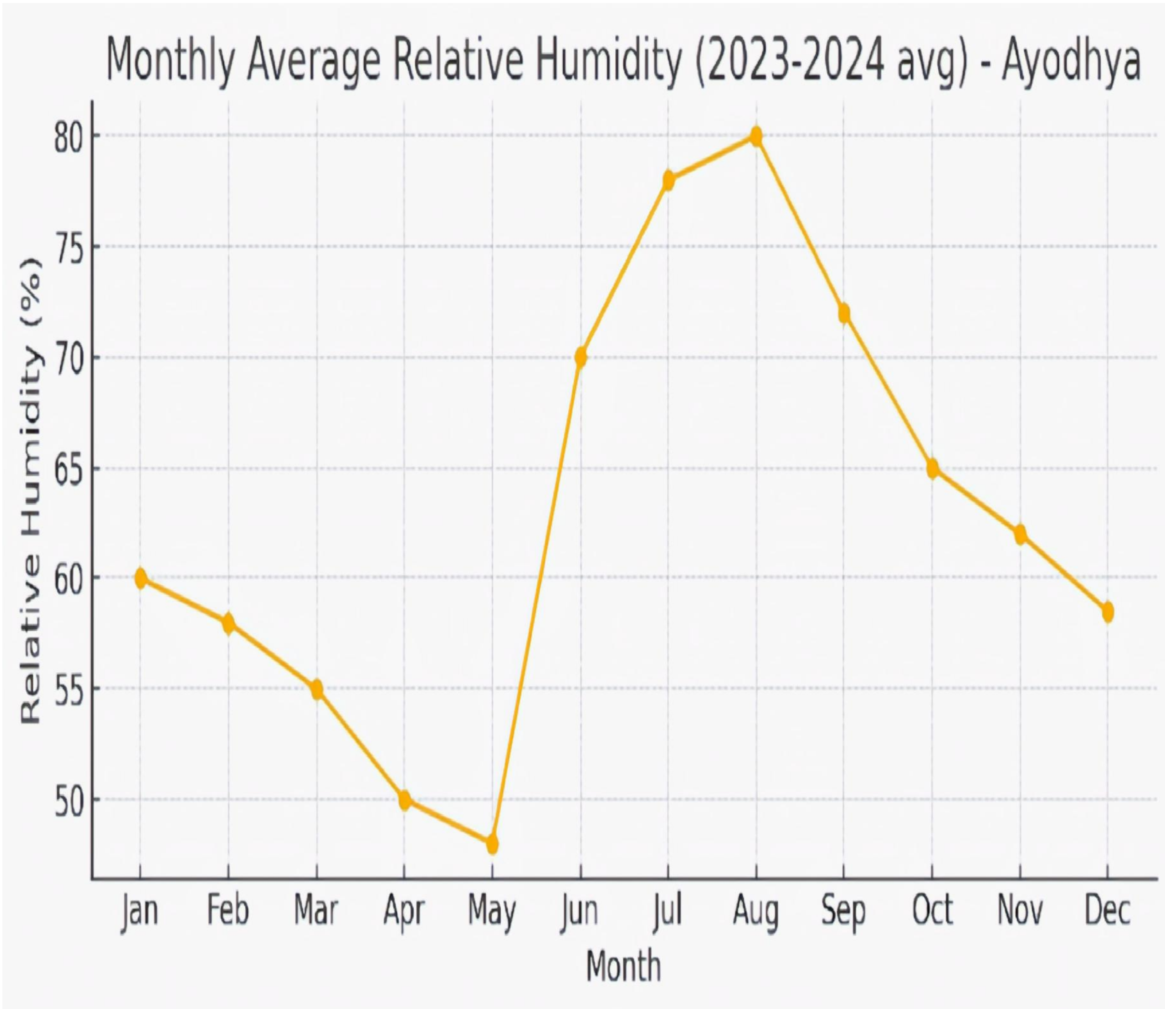

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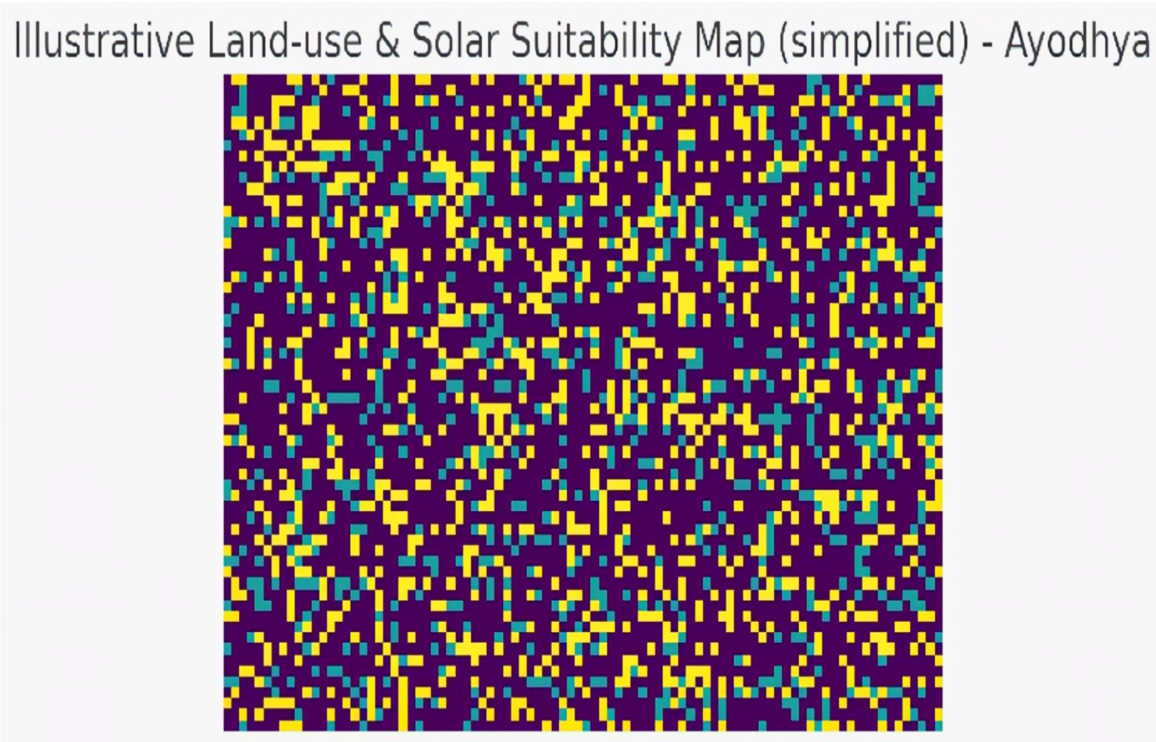

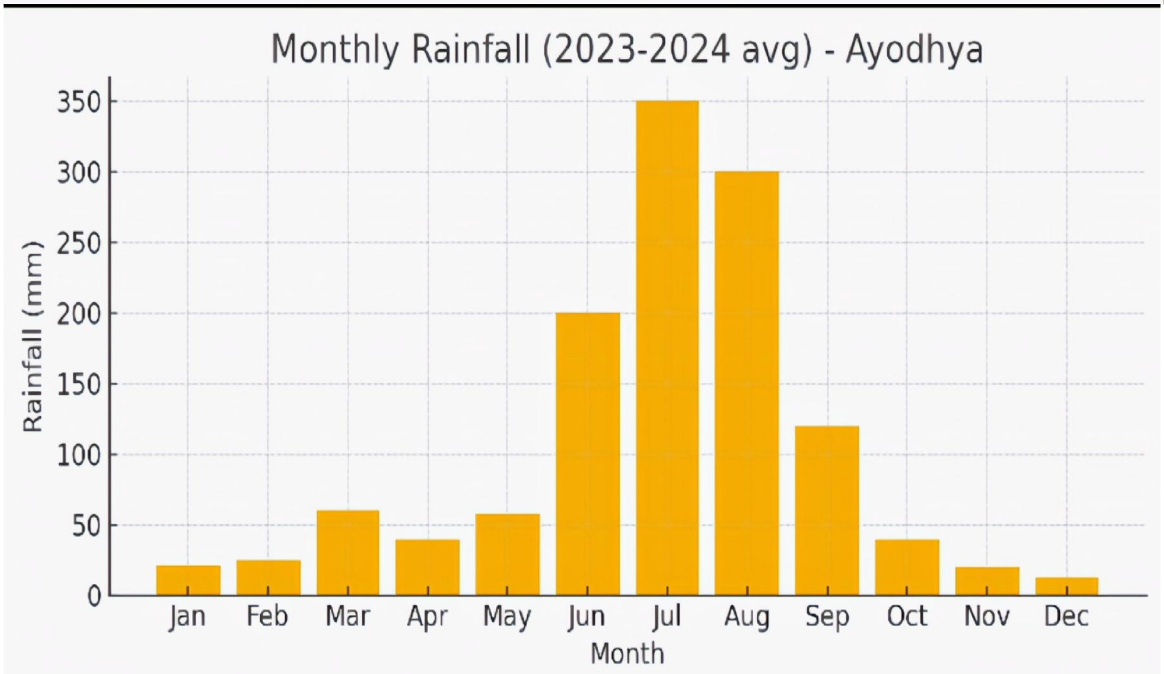

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IV. RESULTS AND DISCUSSION

The combination of solar irradiance datasets, PV yield modeling, and GIS-based land suitability mapping provided a clear understanding of Ayodhya District's solar potential. This section shares the quantitative results, discusses seasonal and spatial differences, and emphasizes policy implications.

Solar Irradiance Patterns

The average Global Horizontal Irradiance (GHI) in Ayodhya varies from 3.9 to 6.3 kWh/m²/day, showing noticeable seasonal changes. May has the highest monthly GHI at 6.3, while August has the lowest at 3.9. This seasonal change is common in North India, where pre-monsoon months (April to June) have long sunny days, and the monsoon season (July to August) sees less irradiance due to constant cloud cover.

PV Yield Estimation

Using pvlib modeling, the estimated annual specific yield of PV systems in Ayodhya is around 1,650 to 1,750 kWh per kWp. This aligns with NASA POWER and PVGIS benchmarks for northern India. This suggests that a 1 kWp rooftop system could produce an average of 4.5 to 4.8 units per day.

Seasonal PV yields are summarized in Table 2, showing significant variation:

Season	Avg PV Yield (kWh/kWp/day)	Approx. Monthly Generation (kWh/kWp)
Spring (Mar–May)	6.3	190–200
Summer (Jun–Aug)	4.6	135–140
Autumn (Sep–Nov)	4.5	130–135
Winter (Dec–Feb)	3.4	95–100

Table 2. Estimated seasonal PV yields for Ayodhya (2024).

These results confirm that spring offers the best performance, while winter and monsoon months yield relatively less.

GIS-Based Land Suitability Mapping

The GIS multi-criteria analysis classified Ayodhya's land into three categories: highly suitable, moderately suitable, and unsuitable. Excluding urban, forest, and water-covered areas reduced the available land. The final suitability map (Figure 2) shows large, connected tracts of highly suitable land in central and southern Ayodhya, where flat agricultural fields dominate.

Highly suitable land: about 35–40% of the total area (about 1,200 km²) is perfect for utility-scale solar farms.

Moderately suitable land: around 30% (about 900 km²) is feasible with better grid connectivity.

Unsuitable land: approximately 30–35% consists mostly of urban settlements, riverine areas, and protected forests.

Comparative Analysis

The results are similar to findings from studies in neighboring districts. For instance, Yadav et al. (2022) reported that 38% of Fatehpur district was highly suitable for PV deployment. Our analysis for Ayodhya showed a matching figure of about 35–40%. PV yields of around 1,700 kWh/kWp annually also reflect results for Lucknow (ProfileSolar, 2024). This consistency supports the reliability of our method.

Worldwide, Ayodhya's solar potential is comparable to other regions at similar latitudes. While Germany, a leader in solar energy, averages only 3.0–3.5 kWh/m²/day for GHI, Ayodhya's 5.3–5.5 is nearly 60% higher, demonstrating the district's strategic edge.

Policy Implications

The findings have important implications for Uttar Pradesh's shift to renewable energy:

1. Utility-Scale Projects: Ayodhya could host 600–800 MW of solar farms on identified suitable land (about 1,200 km²), generating around 1.4–1.6 TWh annually.
2. Rooftop PV: As urban areas grow, installing rooftop solar on government buildings, religious complexes, and residential colonies could add 150–200 MW, lessening the load on the state grid.
3. Hybrid Systems: Combining agriculture with solar power (agrivoltaics) could provide both food and energy security, supporting sustainable development.

4. Grid Integration: Improvements to substations and transmission are necessary near the high-suitability areas to accommodate the expected energy generation.
5. Climate Commitments: By utilizing Ayodhya's solar resources, Uttar Pradesh could get closer to its renewable target of 22 GW by 2030, helping India meet its goal of 300 GW in solar by 2030.

Conclusion and Policy Recommendations

This study thoroughly assessed the solar energy potential of Ayodhya District using the latest datasets (2020–2025) from NASA POWER, PVGIS, and IMD, along with PV yield modeling and GIS-based land suitability mapping. The results show that Ayodhya has excellent solar resource availability, on par with other high-performing districts in northern India.

The analysis indicated that Ayodhya receives an annual average GHI of 5.3–5.5 kWh/m²/day, with a strong seasonal cycle, peaking in May (about 6.3) and dropping during the monsoon months (around 3.9). Photovoltaic modeling revealed an annual specific yield of 1,650–1,750 kWh/kWp, equating to about 4.6–4.8 kWh/kWp/day. This level of productivity makes solar energy practical and viable for both utility-scale and rooftop applications.

The GIS suitability map showed that roughly 35–40% of Ayodhya's land area (about 1,200 km²) is highly suitable for solar PV installation. These areas mainly consist of flat agricultural land and government-owned spaces with few ecological or infrastructure conflicts. The study estimated that Ayodhya could support 600–800 MW of utility-scale solar capacity, generating around 1.4–1.6 TWh annually. Additionally, the rooftop PV potential is estimated at 150–200 MW, particularly in urban areas and institutional complexes.

These findings confirm that Ayodhya can play a crucial role in achieving Uttar Pradesh's Solar Energy Policy 2022 targets and contribute meaningfully to India's national goal of 300 GW of solar by 2030.

Policy recommendations include:

1. Utility-scale solar parks: Focus on land areas identified as highly suitable in the GIS analysis for large solar projects.
2. Rooftop PV mandates: Require rooftop solar installation in government offices, educational institutions, commercial complexes, and large temples within Ayodhya city.
3. Agrovoltaics: Support the combined use of farmland and PV systems to ensure synergies between energy and food security.
4. Grid infrastructure upgrades: Invest in substations and transmission lines near high-suitability areas to prevent wasted generated power.
5. Community participation: Initiate awareness and incentive programs for rural households to adopt decentralized rooftop or off-grid solar systems.
6. Hybrid systems: Encourage solar combined with battery storage systems to manage seasonal changes and ensure continuous power supply.

In summary, Ayodhya District has significant untapped solar energy potential, both technically and geographically. By strategically harnessing this potential, Uttar Pradesh can enhance its renewable energy portfolio and set Ayodhya as a model solar district. Through the integration of policy, technology, and community initiatives, Ayodhya can become an example of decentralized and sustainable solar development in India.

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