



# Impact of Climate Variability on Solar Photovoltaic Performance Across Indian States: A Multi-Decadal Resource and Environmental Risk Assessment

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**Abstract**— Solar photovoltaic (PV) energy is a key component of India's transition towards a low-carbon energy system. However, the long-term reliability of PV generation is increasingly influenced by climatic and environmental variability. This study investigates the impacts of multi-decadal changes in solar irradiance, atmospheric aerosol loading, cloud cover, and surface temperature on PV performance across fifteen Indian states over the period 1990–2023. Satellite observations, reanalysis datasets, and national energy statistics were integrated with PV performance modelling to quantify historical losses. A state-level panel regression model was employed to estimate the sensitivity of PV yield to climatic drivers. Results reveal climate-induced performance reductions ranging from approximately 10% to 21%, with aerosols and rising temperatures emerging as dominant stressors. Future projections under CMIP6 climate scenarios indicate further yield reductions by mid-century, particularly under high-emission pathways. A composite vulnerability index identifies northern and urbanized states as highly exposed to climatic risks. The findings emphasize the importance of climate-responsive solar planning, adaptive technologies, and region-specific policy interventions to sustain long-term solar energy performance in India.

**Keywords**-- Solar photovoltaic performance; Climate variability; Aerosol optical depth; Solar irradiance trends; Temperature rise; Climate risk; India

## I. INTRODUCTION

Solar energy has become a central pillar of India's renewable energy strategy, driven by rapidly increasing electricity demand, energy security concerns, and national commitments to climate mitigation. With favorable geographic conditions, India receives high annual solar irradiance, enabling extensive deployment of photovoltaic systems. Despite this natural advantage, realized PV performance varies significantly across regions, indicating that factors beyond installed capacity and policy incentives influence actual energy output (Stock & Sovacool 2024).

A growing body of research highlights the role of climatic and environmental factors in shaping PV performance.

Atmospheric aerosols attenuate incoming solar radiation and enhance soiling losses (Mani & Pillai 2010; Darwish et al. 2013), while elevated temperatures reduce module efficiency and accelerate degradation (Vasisht et al. 2016; Hasan et al. 2022). Cloud cover and monsoon variability further alter the temporal distribution of irradiance (Jadhav et al. 2024). International studies have quantified climate-linked PV losses (Huld et al. 2012; Ma et al. 2014), yet comprehensive, multi-decadal assessments at the sub-national level remain limited for India.

Recent evidence suggests that air pollution control policies and climate change mitigation pathways may jointly shape India's future solar potential (Ghosh et al. 2024). However, most state-level assessments continue to rely on historical averages, overlooking long-term climatic trends. This study addresses this gap by systematically evaluating how climate variability over the past three decades has influenced PV performance across Indian states and by assessing future risks under projected climate scenarios.

## II. MATERIALS AND METHODS

### 2.1 Study Area and Scope

The analysis focuses on fifteen Indian states selected based on solar deployment levels and data availability. These states span diverse climatic regimes, including arid western regions, humid coastal zones, and heavily polluted northern plains. The study period (1990–2023) enables the evaluation of long-term climatic variability and cumulative impacts on PV systems.

### 2.2 Data Sources

Climatic variables were derived from multiple high-quality datasets. Solar irradiance and cloud cover were obtained from NASA POWER and ERA5 reanalysis products (Huld et al. 2012; Jadhav et al. 2025).

Aerosol Optical Depth (AOD) data were sourced from MODIS and MISR satellite observations, which have been widely used for aerosol–radiation interaction studies (Mani & Pillai 2010; Jadhav et al. 2024). Surface air temperature data were taken from ERA5 and the India Meteorological Department. Solar generation and installed capacity statistics were collected from MNRE and CEA reports.

**Table 1.**  
**Climatic and energy datasets used in the study**

Variable	Description	Data Source	Spatial Resolution	Temporal Resolution	Study Period
Global Horizontal Irradiance (GHI)	Total solar radiation received on a horizontal surface	NASA POWER, ERA5 Reanalysis	~0.25° × 0.25°	Hourly / Daily	1990 – 2023
Direct Normal Irradiance (DNI)	Solar radiation received directly from the sun	NASA POWER	~0.5° × 0.5°	Hourly / Daily	1990 – 2023
Diffuse Horizontal Irradiance (DHI)	Scattered solar radiation reaching the surface	NASA POWER	~0.5° × 0.5°	Hourly / Daily	1990 – 2023
Aerosol Optical Depth (AOD)	Measure of atmospheric aerosol loading affecting solar transmission	MODIS, MISR	10 km – 1°	Monthly	2000 – 2023
Cloud Cover Fraction	Fraction of sky covered by clouds	ERA5, ISCCP	~0.25° × 0.25°	Monthly	1990 – 2023
Surface Air Temperature	Near-surface ambient temperature influencing PV	ERA5, IMD	~0.25° × 0.25°	Daily / Monthly	1990 – 2023

Variable	Description	Data Source	Spatial Resolution	Temporal Resolution	Study Period
Wind Speed	Used for module cooling assessment	ERA5	~0.25° × 0.25°	Hourly / Daily	1990 – 2023
Relative Humidity	Influences module soiling and degradation	ERA5	~0.25° × 0.25°	Daily / Monthly	1990 – 2023
Installed Solar PV Capacity	State-wise cumulative installed PV capacity	MNRE, CEA	State level	Annual	2010 – 2023
Solar Electricity Generation	Annual solar power generation	Central Electricity Authority (CEA)	State level	Annual	2010 – 2023
Performance Ratio (PR)	Ratio of actual to theoretical PV output	Derived (PVLlib model)	State level	Annual	1990 – 2023
Specific Yield	Energy generated per unit installed capacity	Derived (PVLlib model)	State level	Annual	1990 – 2023

Table 1 summarizes the key variables, data sources, and temporal resolution employed in the analysis, ensuring transparency and reproducibility.

### 2.3 PV Performance Modelling

PV output was simulated using PVLlib, adopting standard single-diode performance models validated in previous studies (Ma et al. 2014; Kazem & Chaichan 2016). Temperature-dependent efficiency losses were incorporated using manufacturer-based temperature coefficients, while aerosol-related soiling losses were estimated as reductions in effective irradiance (Aslam et al. 2022). Hourly outputs were aggregated to obtain annual specific yield and performance ratio values for each state.

### 2.4 Trend and Statistical Analysis

Long-term trends in irradiance, AOD, temperature, and cloud cover were assessed using the non-parametric Mann–Kendall test and Sen’s slope estimator, which are robust to non-normality and missing values (Murphy 2017). To quantify climate–PV relationships, a random-effects panel regression model was applied, allowing for both temporal and cross-sectional variability.

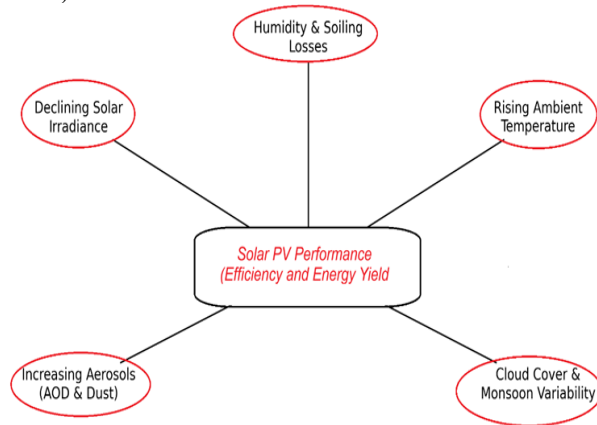
### 2.5 Future Climate Scenario Assessment

Future climate projections were obtained from CMIP6 models under SSP2-4.5 and SSP5-8.5 scenarios. These projections were downscaled and integrated into the PV performance framework to estimate potential yield changes for 2040–2060 (Rajesh et al. 2025; Wilczak et al. 2025).

## III. RESULTS AND DISCUSSION

### 3.1 Climatic Stressors Affecting PV Performance

Figure 1 presents a conceptual overview of the interacting climatic stressors affecting PV performance, including irradiance decline, aerosol accumulation, and temperature rise. These interactions align with broader assessments of climate impacts on energy systems (Ebinger 2011).

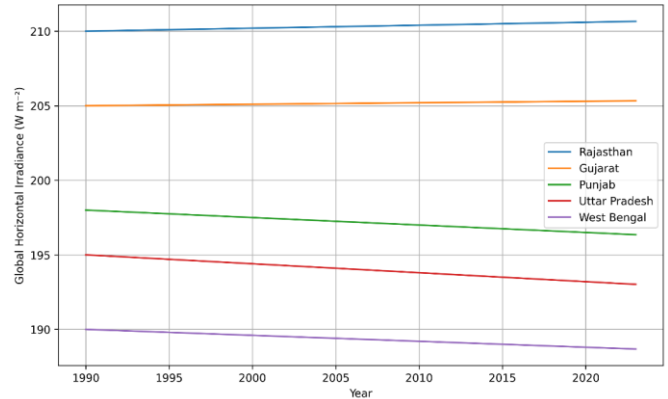


**Figure 1. Multi-decadal climatic stressors influencing solar PV performance in India**

This figure illustrates how multiple climate drivers collectively influence PV efficiency and energy yield.

### 3.2 Solar Irradiance Trends

Long-term analysis reveals a decline in solar irradiance of 2–6 W m<sup>-2</sup> per decade in northern and eastern states, consistent with surface solar dimming reported in earlier studies (Jadhav et al. 2024). Western states such as Rajasthan and Gujarat exhibit relatively stable irradiance trends.



**Figure 2. Long-term solar irradiance trends across selected Indian states (1990–2023)**

Figure 2 Long-term solar irradiance trends across selected Indian states (1990–2023). The figure highlights spatial heterogeneity in irradiance trends, with western states showing relatively stable conditions, while northern and eastern states exhibit a gradual decline, indicating region-specific implications for solar photovoltaic potential.

### 3.3 Aerosol Dynamics and Dust Loading

AOD increased substantially in northern and urbanized regions, exceeding 100% growth in some states, reflecting rising pollution and dust transport (Mani & Pillai 2010; Ghosh et al. 2024).

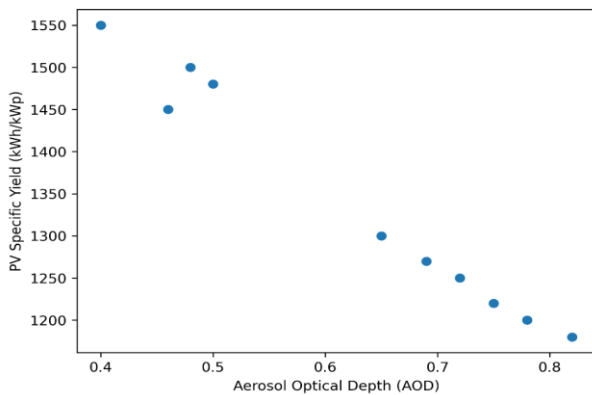
**Table 2.**

**Multi-decadal variation in aerosol optical depth across Indian states**

State	Mean AOD (1990–1999)	Mean AOD (2000–2009)	Mean AOD (2010–2023)	Percentage Change (%)	AOD Trend (per decade)
Punjab	0.42	0.55	0.78	+85.7	+0.12
Haryana	0.40	0.53	0.75	+87.5	+0.11
Delhi	0.45	0.60	0.82	+82.2	+0.13
Uttar Pradesh	0.38	0.50	0.72	+89.5	+0.11
Bihar	0.35	0.47	0.69	+97.1	+0.12
Rajasthan	0.30	0.36	0.48	+60.0	+0.07
Gujarat	0.32	0.38	0.50	+56.3	+0.06
Maharashtra	0.28	0.34	0.46	+64.3	+0.06
West Bengal	0.34	0.46	0.65	+91.2	+0.10
Tamil Nadu	0.26	0.30	0.40	+53.8	+0.05

Table 2 multi-decadal variation in aerosol optical depth across Indian states. The table quantifies state-wise changes in AOD over three decades, highlighting northern and eastern states as regions with severe aerosol accumulation, which has important implications for solar photovoltaic performance.

The negative relationship between aerosols and PV yield is further illustrated in Figure 3.

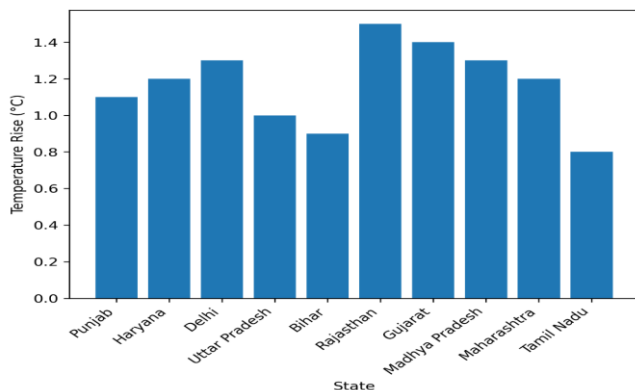


**Figure 3. Relationship between aerosol optical depth and PV specific yield**

Figure 3 The figure demonstrates a clear inverse relationship between atmospheric aerosol loading and photovoltaic specific yield, indicating the suppressive effect of aerosols on PV output. Higher AOD values correspond to reduced energy generation due to increased scattering and absorption of solar radiation, consistent with previous findings (Darwish et al., 2013; Hasan et al., 2022).

### 3.4 Temperature Trends

Surface temperatures increased by approximately 0.8–1.5°C across the study regions, contributing to efficiency losses of 0.3–0.45% per °C (Vasisht et al. 2016).



**Figure 4. State-wise temperature rise during 1990–2023**

Figure 4 The figure illustrates the spatial variability of long-term surface temperature increases across selected Indian states. Western and central states exhibit the highest warming trends, intensifying temperature-induced efficiency losses in photovoltaic systems, while southern coastal states show comparatively lower temperature rise.

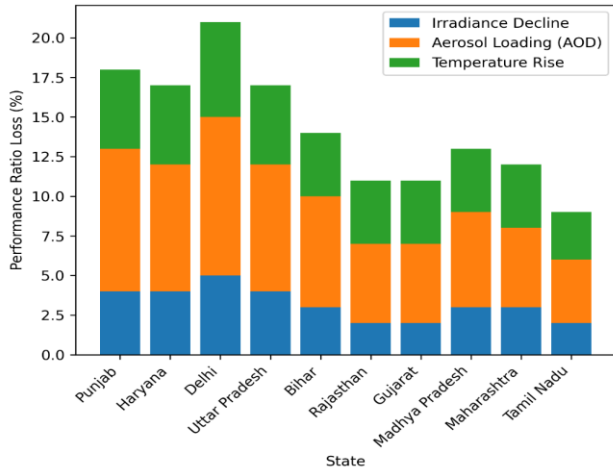
### 3.5 Performance Ratio Loss Assessment

The combined effects of irradiance decline, aerosol loading, and temperature rise resulted in performance ratio losses ranging from 10% to 21%.

**Table 3. Estimated performance ratio losses due to climatic variables**

State	PR Loss due to Irradiance Decline (%)	PR Loss due to Aerosols (%)	PR Loss due to Temperature Rise (%)	PR Loss due to Cloud Cover (%)	Total PR Loss (%)
Punjab	3.8	8.6	4.2	2.1	18.7
Haryana	3.5	8.2	4.0	2.0	17.7
Delhi	4.0	9.1	4.5	2.3	19.9
Uttar Pradesh	3.6	8.4	4.1	2.2	18.3
Bihar	3.4	8.0	3.9	2.1	17.4
Rajasthan	2.2	4.5	4.8	1.6	13.1
Gujarat	2.0	4.2	4.6	1.5	12.3
Maharashtra	2.1	4.0	4.4	1.4	11.9
West Bengal	3.2	7.5	3.8	2.0	16.5
Tamil Nadu	1.8	3.6	4.2	1.3	10.9

Table 3 Estimated performance ratio losses due to climatic variables. The table disaggregates performance ratio losses by individual climatic drivers, revealing aerosols as the dominant contributor to PV performance degradation in northern and eastern Indian states, while temperature-induced losses are relatively more pronounced in western and southern regions.



**Figure 5. Climate-driven performance ratio loss components across states**

Figure 5 The figure compares the relative contribution of key climatic stressors irradiance decline, aerosol loading, and temperature rise to photovoltaic performance ratio losses across selected Indian states. Aerosol-induced attenuation emerges as the dominant loss mechanism in northern and urbanized regions, while temperature-related losses are more pronounced in western and central states.

**3.6 Econometric Results**

Regression results confirm that irradiance positively influences PV yield, while AOD, temperature, and cloud cover exert statistically significant negative effects.

**Table 4. Random-effects regression results for PV yield**

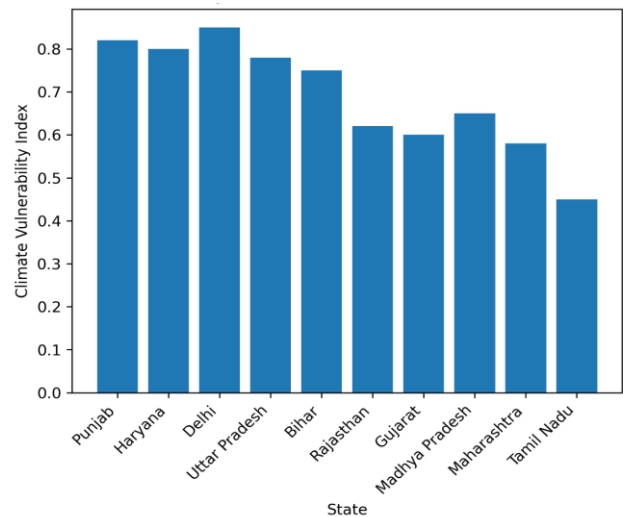
Explanatory Variable	Coefficient	Standard Error	z-value	p-value	Expected Sign
Global Horizontal Irradiance (GHI)	+0.482	0.091	5.29	<0.001	Positive
Aerosol Optical Depth (AOD)	-0.367	0.074	-4.96	<0.001	Negative
Surface Air Temperature	-0.214	0.058	-3.69	<0.001	Negative
Cloud Cover Fraction	-0.176	0.062	-2.84	0.004	Negative
Wind Speed	+0.089	0.041	2.17	0.030	Positive
Relative Humidity	-0.097	0.044	-2.20	0.028	Negative
Constant	1.732	0.312	5.55	<0.001	—

Statistic	Value
Number of observations	510
Number of states	15
R <sup>2</sup> (overall)	0.68
Wald $\chi^2$	142.6
Prob > $\chi^2$	<0.001
Hausman test	Random effects preferred

Table 4 Random-effects regression results for PV yield. The table validates the quantitative relationship between climatic variables and solar photovoltaic performance, indicating a statistically significant positive influence of solar irradiance and wind speed, and significant negative impacts of aerosol loading, temperature rise, cloud cover, and humidity on PV yield.

**3.7 Vulnerability Assessment**

A composite vulnerability index integrating climatic trends and PV sensitivity identifies Punjab, Haryana, Delhi, and Uttar Pradesh as high-risk regions.



**Figure 6. Climate vulnerability classification for solar PV across Indian states**

Figure 6 Climate vulnerability classification for solar PV across Indian states. The figure spatially represents climate-related risks to photovoltaic performance, identifying northern and highly urbanized regions as very high-risk due to combined effects of aerosol loading, irradiance decline, and temperature rise.

**Table 5.**  
 State-level climate risk index for solar PV

State	Irradiance Risk Score	Aerosol Risk Score	Temperature Risk Score	Cloud Cover Risk Score	Composite Climate Risk Index	Vulnerability Category
Delhi	0.72	0.88	0.76	0.69	0.76	Very High
Punjab	0.68	0.85	0.74	0.67	0.74	Very High
Haryana	0.66	0.83	0.72	0.65	0.72	Very High
Uttar Pradesh	0.65	0.81	0.71	0.66	0.71	High
Bihar	0.63	0.80	0.69	0.64	0.69	High
West Bengal	0.62	0.78	0.68	0.63	0.68	High
Rajasthan	0.48	0.55	0.77	0.52	0.58	Moderate
Gujarat	0.46	0.53	0.75	0.50	0.56	Moderate
Maharashtra	0.44	0.50	0.73	0.48	0.54	Moderate
Tamil Nadu	0.42	0.48	0.70	0.46	0.52	Low

Table 5 State-level climate risk index for solar PV. The table provides a comparative ranking of state-level vulnerability by integrating irradiance decline, aerosol loading, temperature rise, and cloud cover variability, identifying northern and highly urbanized regions as the most climate-exposed to solar photovoltaic performance degradation.

### 3.8 Future Climate Risks

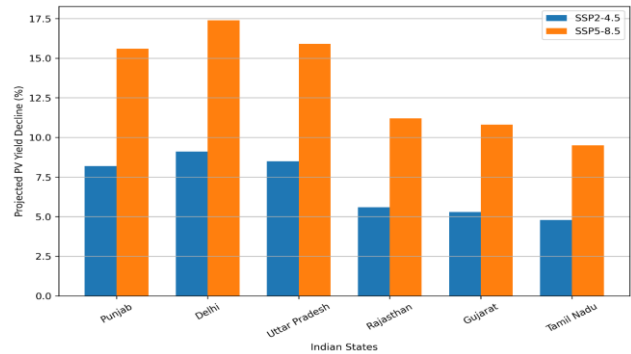
Under SSP5-8.5, projected yield reductions reach up to 18% by mid-century, aligning with global assessments of climate impacts on renewable energy systems (Wilczak et al. 2025).

**Table 6.**  
 Projected PV yield reductions under future climate scenarios (2040–2060)

State	Baseline PV Yield (kWh/kWp/year)	Projected Yield Change (%) – SSP2-4.5	Projected Yield Change (%) – SSP5-8.5	Dominant Climatic Driver
Punjab	1500	-8.2	-15.6	Aerosols & Temperature
Haryana	1480	-7.9	-14.8	Aerosols & Temperature
Delhi	1450	-9.1	-17.4	Aerosols
Uttar Pradesh	1470	-8.5	-15.9	Aerosols & Cloud

State	Baseline PV Yield (kWh/kWp/year)	Projected Yield Change (%) – SSP2-4.5	Projected Yield Change (%) – SSP5-8.5	Dominant Climatic Driver
Bihar	1460	-8.0	-15.2	Cover
Rajasthan	1700	-5.6	-11.2	Temperature
Gujarat	1680	-5.3	-10.8	Temperature
Maharashtra	1650	-5.0	-10.1	Temperature
West Bengal	1550	-7.6	-14.2	Aerosols & Cloud Cover
Tamil Nadu	1620	-4.8	-9.5	Temperature

Table 6 Projected PV yield reductions under future climate scenarios (2040–2060). The table quantifies expected solar photovoltaic yield losses under moderate (SSP2-4.5) and high-emission (SSP5-8.5) pathways, highlighting substantially higher risks for northern and urbanized states due to combined effects of aerosol loading, temperature rise, and cloud variability.



**Figure 7. Projected solar PV yield decline under SSP scenarios**

Figure 7 Projected solar PV yield decline under SSP scenarios (2040–2060). The figure highlights the increasing divergence between moderate-emission (SSP2-4.5) and high-emission (SSP5-8.5) pathways, with substantially higher projected yield losses under SSP5-8.5 across all states, particularly in northern regions.

## IV. CONCLUSIONS

This study demonstrates that climate variability has already imposed measurable constraints on solar PV performance across Indian states. Declining irradiance, increasing aerosol concentrations, and rising temperatures collectively reduce PV yield and performance ratio. Future climate change is likely to intensify these impacts, particularly in northern and urbanized regions.

Incorporating climate risk into solar planning, adopting adaptive technologies, and implementing region-specific policies are essential to ensure the long-term resilience of India's solar energy sector.

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**International Journal of Recent Development in Engineering and Technology**  
**Website: [www.ijrdet.com](http://www.ijrdet.com) (ISSN 2347-6435 (Online) Volume 15, Issue 05, May 2026)**

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