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Research Article

Comparative Analysis of Solar Energy Generation across Key Indian States

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Abstract

The pursuit of the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), represents a global response to pressing environmental challenges. As the world's fastest-growing economy, India plays a pivotal role in the global clean energy transition. Its remarkable expansion in renewable energy, especially solar power, is central to its commitment to ensuring access to affordable, reliable, and sustainable energy for all. The five leading states in India's renewable energy transition, Rajasthan, Gujarat, Tamil Nadu, Karnataka, and Maharashtra, collectively dominate the nation's clean power infrastructure. Together, they account for 63.19 per cent of the country's total installed renewable electricity capacity, underscoring their pivotal role in India's shift toward sustainable energy. Their influence is even more pronounced within the solar power sector alone, where they represent 73.17 per cent of the nation's total installed solar capacity. This concentration highlights both the geographic and strategic centrality of these states in driving India's renewable energy agenda and achieving its national and international climate commitments. The analysis identifies three distinct developmental phases: early dominance by Rajasthan and Gujarat in 2014-18, the rapid ascent of Karnataka in 2018-22, and a phase of consolidated growth marked by Maharashtra's strong surge in recent years. These divergent trajectories are examined through the lens of state-specific drivers, including policy interventions, infrastructure, and market dynamics. Notably, Karnataka's exceptional growth, achieving the highest compound annual growth rate despite a modest start, highlights the impact of proactive state-level policy and regulatory support.

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1. INTRODUCTION

Globally, electricity generation is dominated by fossil fuels (coal, gas, and oil), followed by hydroelectric power, nuclear energy, and renewable sources such as wind and solar. However, reliance on fossil fuels poses significant challenges, including depleting reserves and substantial carbon dioxide emissions that contribute to global warming. As a result, governments worldwide are focusing on increasing the use of renewable energy sources to mitigate these issues and create a more sustainable energy future. These sources include solar, wind, hydro, geothermal, and biomass. These resources are naturally replenished on a human timescale and are considered crucial for reducing carbon emissions.

India receives abundant solar radiation, with most areas averaging 4-7 kWh/m²/day and 250-300 sunny days annually. The northwestern regions, particularly Rajasthan and Gujarat, experience exceptionally high solar insolation, exceeding 6.0 kWh/m²/day, due to their desert climates and minimal cloud cover. In contrast, the northeastern states and the Western Ghats receive relatively lower isolation due to higher rainfall and humidity. India's proximity to the equator and extensive coastline further enhance its solar potential, making it an attractive market for solar energy development, driven by declining technology costs and supportive policies. India's ambitious transition to renewable energy is geographically decentralized, with solar power at its forefront. While national targets and policies provide a unifying framework, the realization of solar potential is shaped by diverse subnational contexts. This study compares solar electricity generation from 2014-15 to 2024-25 across five leading Indian states: Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Maharashtra. These states collectively represent a spectrum of India's solar landscape, from early adopters in arid zones to late-stage accelerators in plateau regions.

2. REVIEW OF LITERATURE

Khare Saxena, A., Saxena, S., & Sudhakar, K., *et al.* (2024) [2]. This paper provides a comprehensive overview of India's solar energy policy framework, growth trajectory, and prospects, emphasizing the critical role of government initiatives in addressing energy security, climate change, and sustainable development. It reviews national and state-level policies. The study highlights India's vast solar potential, significant achievements in utility-scale solar parks and decentralized applications, and the sharp decline in solar tariffs due to technological advancement and policy support. At the same time, it identifies persistent challenges related to grid integration, DISCOM finances, land availability, financing, and implementation delays. Overall, the paper concludes that India's solar sector is largely policy-driven and well-positioned to meet long-term renewable energy targets, provided institutional coordination, infrastructure strengthening, and investment stability are sustained.

Ramapati, S., & Gupta, S., *et al.* (2024) [3]. This study examines the adoption of rooftop solar systems in Gujarat, focusing on

opportunities and challenges. Using survey data from Patan and Mehsana districts, it finds strong correlations between capital cost, subsidies, maintenance, and awareness, highlighting the need for policy support, financing access, and awareness to ensure sustainable rooftop solar growth.

Venkatakrishnan, G. R., & Rengaraj, R., *et al.* (2014) [6]. This paper reviews the status and potential of solar energy in India, emphasizing the transition from conventional to renewable energy sources. It discusses solar energy technologies, policy initiatives, state-wise capacity distribution, and investment trends, concluding that solar power is vital for India's future energy security and sustainable development.

Surender Kumar Sharma., *et al.* (2024) [1]. This paper examines the role of solar photovoltaic systems in driving India's economic growth by enhancing energy security, creating employment opportunities, stimulating investment, and fostering technological advancements. It highlights policy support, case studies such as Rewa and Kamuthi solar parks, and concludes that solar PV integration is vital for sustainable, long-term economic development in India.

Bhatt, H., & Pandya, M., *et al.* (2023) [4]. This paper analyses renewable energy and environmental policies in Gujarat, highlighting the state's leadership in solar and wind energy development. It examines policy initiatives, institutional support, and environmental impacts, concluding that effective governance and investment-friendly policies have significantly contributed to Gujarat's sustainable energy growth.

Saradva, A. R., *et al.* (2021) [5]. This review examines India's rooftop solar energy potential, policy framework, and growth trends under initiatives like the National Solar Mission. It highlights achievements, global comparisons, and major challenges such as high upfront costs, limited awareness, manufacturing gaps, and workforce constraints, concluding that supportive policies are vital for sustainable expansion.

3. RESEARCH METHODOLOGY

This study uses a mixed-methods, comparative case study design analyzing five high-capacity solar states, Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Maharashtra, from 2014 to 2024. It integrates quantitative analysis of secondary data on capacity, generation, and growth trends, CAGR, with a qualitative assessment of policy, geographical, and infrastructural factors to evaluate diverse solar development models in India.

4. OBJECTIVES

This study aims to analyze and compare decade-long trends from 2014-15 to 2024-25 in solar electricity generation across Rajasthan, Gujarat, Tamil Nadu, Karnataka, and Maharashtra.

To quantify growth percentage and Compound annual Growth Rate, and correlate growth patterns with state-specific factors like geographical advantages, policy frameworks, and infrastructure developments.

DATA ANALYSIS

This paper presents a comparative analysis of solar energy generation across five major Indian states, Rajasthan, Gujarat, Tamil Nadu, Karnataka, and Maharashtra, over eleven years

from 2014-15 to 2024-25. The data reveals varying growth patterns, installed capacities, and contributions to India’s renewable energy transition.

Table 1: Installed Capacity under solar power renewable energy storage from 2014-15 to 2024-25 (in MW)

Year	Rajasthan	Gujarat	Tamil Nadu	Karnataka	Maharashtra
2014 -15	1000.23	1011.69	156.83	83.95	363.77
2015 -16	1346.09	1137.82	1090.57	158.41	390.88
2016 -17	1907.99	1278.19	1728.52	1045.30	460.69
2017 -18	2431.66	1626.19	1950.86	4965.25	1251.4
2018 -19	3364.03	2478.32	2618.71	6120.76	1648.46
2019 -20	5275.27	2986.77	3961.56	7306.18	1835.62
2020 -21	5925.6	4469.87	4527.47	7383.88	2323.79
2021-22	12564.87	7180.03	5067.18	7590.81	2631.02
2022 -23	17055.7	9254.56	6736.43	8241.40	4722.9
2023 -24	21347.58	13544.88	8211.38	8544.68	6249.67
2024 -25	28286.47	18496.66	10153.58	9679.66	10687.27
Growth in % (2014-15 to 2024-25)	2728.00%	1728.29%	6374.26%	11430.27%	2837.92%
CAGR (Compound Annual Growth Rate in %) (2014-15 to 2024-25)	39.68%	33.72%	51.75%	60.76%	40.22%

(Source: Renewable energy statistics 2024-25.)

Rajasthan and Gujarat started as the leading solar producers in 2014-15, with generation values of 1000.23 and 1011.69 MW, respectively. By 2024-25, Rajasthan surged ahead to 28,286.47 MW, maintaining its top position. Gujarat also showed strong growth, reaching 18,496.66 MW. Karnataka, though starting modestly at 83.95 MW in 2014-15, exhibited the most dramatic growth, surpassing all except Rajasthan by 2024-25 with 9,679.66 MW. This remarkable rise is reflected in its high growth percentage of 114.30 percent over the period. Tamil Nadu began with a moderate 156.83 MW and grew steadily to 10,153.58 MW by 2024-25, showing the second-highest growth rate of 63.74 percent after Karnataka. Maharashtra started at 363.77 MW and reached 10,687.27 MW in 2024-25, recording a steady but relatively slower growth percentage of 28.38 percent compared to the others.

Table 2: State-wise solar power renewable energy growth percent & Compound Annual Growth Rate from 2014-15 to 2024-25

State	Growth % (2014-15 to 2024-25)	CAGR (%)
Karnataka	114.30	0.6076
Tamil Nadu	63.74	0.5175
Rajasthan	27.28	0.3968
Maharashtra	28.38	0.4022
Gujarat	17.28	0.3372

(Source: Renewable energy statistics 2024-25.)

Karnataka leads in both growth percentage and Compound Annual Growth, indicating the fastest and most consistent annual expansion in solar generation.

Gujarat, despite its high absolute generation, shows the lowest growth percentage and CAGR, suggesting early adoption followed by relatively slower growth compared to others. Rajasthan and Maharashtra show moderate growth rates, moderate growth rates, but Rajasthan’s large base keeps it as the top absolute producer.

Geographical Location of Rajasthan & Solar Resource Potential

Rajasthan occupies a premier geographical position for solar energy generation in India and Asia. The state’s dominant landscape is the Thar Desert, which sprawls across western and northwestern Rajasthan, creating one of the world’s most intense and consistent solar resource zones. This arid to semi-arid region, characterized by minimal cloud cover, low annual rainfall, and vast expanses of flat, barren land, delivers exceptional solar insolation levels averaging 5.8–6.2 kWh/m²/day among the highest in the nation. The solar potential is further enhanced by over 325 clear, sunny days per year and high Direct Normal Irradiance, making it ideal for both photovoltaic and concentrated solar power technologies. Geographically, solar intensity increases from the relatively greener, southeastern districts like Kota toward the hyper-arid northwest Jaisalmer, Bikaner, and Barmer.

Major Solar Park Projects in Rajasthan

1. Bhadla Solar Park, Jodhpur & Jaisalmer districts. Recognized as one of the largest solar parks in the world, Bhadla has a total installed capacity exceeding 2,245 MW. Located in the heart of the Thar Desert, it is characterized by extremely high irradiation, sandy terrain, and the use of advanced dust mitigation and waterless cleaning systems. It serves as a global benchmark for ultra-mega solar project development in arid environments.
2. Pachpadra Solar Park, Barmer district. With a planned capacity of 1,000 MW, this park is being developed near the Pachpadra salt basin. Its notable feature is its integration with salt pan land, demonstrating the use of otherwise non-arable, barren land for large-scale renewable energy generation, thereby minimizing ecological displacement.

- Fatehgarh Solar Park Jaisalmer district An early pioneer, this park has a capacity of over 430 MW and is part of Rajasthan's first wave of utility-scale solar development. It is strategically located to feed power into the Northern Grid and has been instrumental in establishing the state's solar infrastructure and project execution protocols.

Geographical Location of Gujarat & Solar Resource Potential

Gujarat benefits from a distinctive geographical positioning that amplifies its solar energy potential. Bordered by the Arabian Sea to the west and the Rann of Kutch desert to the northwest, the state features diverse topography, including coastal plains, arid deserts, and fertile alluvial regions. This variability creates distinct solar zones: the northwestern districts of Kutch and parts of Banaskantha experience exceptionally high solar insolation levels of 5.8–6.2 kWh/m²/day among the highest in India due to arid desert conditions, minimal cloud cover, and extensive dry, flatlands ideal for large-scale solar installations. Meanwhile, the coastal and southern regions such as Surat and Valsad receive slightly lower irradiation 4.8–5.4 kWh/m²/day owing to higher humidity and maritime influences, yet still offer significant potential for distributed and hybrid energy systems.

Gujarat's proximity to the Tropic of Cancer, combined with over 300 sunny days annually and a strategic location along national energy corridors, enhances its viability for both photovoltaic and concentrated solar power technologies. Moreover, its extensive salt marshlands, Rann, and coastline present unique opportunities for floating solar and coastal solar-wind hybrid projects, positioning Gujarat as a geographically advanced and diversified leader in India's renewable energy landscape.

Major Solar Park Projects in Gujarat

- Charanka Solar Park, Patdi, Patan district One of Asia's first and largest solar parks at its launch, with a capacity exceeding 790 MW. Located in the semi-arid North Gujarat region, it is part of the Gujarat Solar Park Phase-I and is noted for its cluster-based development model, integrating multiple developers in a single, contiguous zone with shared infrastructure.
- Dholera Solar Park Dholera Special Investment Region Planned as an ultra-mega park with a target of 5,000 MW, this project is part of the Dholera Smart City initiative. Its geographic innovation lies in its integration with a planned industrial and urban hub, designed to power a future city while utilizing arid land near the Gulf of Khambhat.
- Raghanesda Solar Park, Banaskantha district. With an operational capacity of 700 MW, this park is situated in a high-insolation zone near the Rajasthan border. It is notable for its advanced single-axis tracking systems and efficient grid connectivity, serving both Gujarat and inter-state energy transfer.

Geographical Location of Karnataka & Solar Resource Potential

Karnataka is distinguished by a topographical gradient that creates a strong eastward increase in solar resource potential. The state extends from the humid, biodiverse Western Ghats along the coast to the expansive, semi-arid Deccan Plateau inland. This elevational and climatic transition results in a clear solar resource dichotomy in the interior plateau districts, such as Tumakuru, Chitradurga, Ballari, and the northern regions of Kalaburagi and Bidar receive high solar insolation of 5.5–6.0 kWh/m²/day with over 300 clear sunny days annually, due to rain shadow effects, lower humidity, and minimal cloud cover. In contrast, the western coastal and Malnad regions, e.g., Dakshina Kannada, Udupi, experience moderate irradiation 4.5–5.2 kWh/m²/day because of heavy monsoon influence, orographic rainfall, and higher cloud persistence. This geographic and climatic contrast enables Karnataka to strategically deploy large-scale solar parks in its sun-rich eastern plains while promoting distributed and rooftop solar in urban and western regions. Moreover, the state's extensive network of reservoirs and irrigation canals in the plateau offers significant potential for floating and canal-top solar, mitigating land use pressures. This geographical diversity, combined with progressive state policies, positions Karnataka as a leader in integrating utility-scale solar with hydrological and agricultural landscapes.

Major Solar Park Projects in Karnataka

- Pavagada Ultra Mega Solar Park Shakti Sthala, Tumakuru With a capacity of 2,050 MW, it is one of the largest solar parks in the world. Its notable geographic and social innovation is the land-pooling model, where over 2,300 farmers lease arid land for 28 years, ensuring income without displacement. Located in the rain-shadow region, it utilizes robotic dry-cleaning to conserve water.
- Koppal Solar Park, Koppal district Developed by Karnataka Power Corporation Limited this park has a capacity of 1,000 MW. Situated in the high-insolation northern plateau, it is integrated with strong grid evacuation infrastructure and supports the state's renewable energy obligations.
- Gadag Solar Park, Gadag district with an operational capacity of 500 MW, this park is located in the central dry zone of Karnataka. It is part of the state's solar park scheme and demonstrates the use of semi-arid, low-yield agricultural land for large-scale solar generation.

Geographical Location of Tamil Nadu & Solar Resource Potential

Tamil Nadu, located in southeastern peninsular India, lies between the Coromandel Coast and the Eastern Ghats, extending inland to the Deccan Plateau. The state generally experiences 250–300 clear or sunny days annually, with solar insolation ranging from 4.5 to 5.8 kWh/m²/day. Regional variation is significant: interior and southern districts such as

Ramanathapuram, Tirunelveli, and Dharmapuri benefit from higher irradiation 5.5–5.8 kWh/m²/day due to arid conditions and minimal cloud cover, while coastal areas like Chennai and Nagapattinam receive slightly lower levels 4.5–5.2 kWh/m²/day because of higher humidity and the northeast monsoon influence.

Major Solar Park Projects in Tamil Nadu

1. Kamuthi Solar Power Project Located in Ramanathapuram district, this is one of the world's largest single-location solar plants, with a capacity of 648 MW. It spans over 2,500 acres, featuring fully robotic panel cleaning systems and grid-connected infrastructure that was completed within just eight months.
2. NLC India Ltd. Solar Plants, Neyveli Situated in Cuddalore district, these plants collectively exceed 709 MW across multiple phases. Located on reclaimed mining land, they demonstrate sustainable land reclamation and repurposing in energy projects and integrate with Neyveli's existing lignite-based power infrastructure.
3. Adani Group Solar Park Ramanathapuram. With an operational capacity of 648 MW at multiple sites in Ramanathapuram, this project supports Tamil Nadu's green energy corridor and is known for its advanced inverter and substation technologies, ensuring efficient power evacuation.

Geographical Location of Maharashtra & Solar Resource Potential

Maharashtra encompasses a geographically diverse landscape that significantly shapes its solar energy profile. The state extends from the narrow Konkan coastal plains along the Arabian Sea to the expansive Deccan Plateau inland, flanked by the Western Ghats Sahyadri range to the west. This topography creates a pronounced rain shadow effect, resulting in markedly different solar regimes: the interior plateau regions, particularly in districts like Solapur, Osmanabad, Beed, and Marathwada, experience high solar insolation levels of 5.5–6.0 kWh/m²/day with over 300 sunny days annually, due to arid and semi-arid conditions and minimal cloud cover.

Major Solar Park Projects in Maharashtra

1. Dhalegaon Solar Park, Solapur Developed by Maharashtra State Power Generation Company (MAHAGENCO), this is one of the state's earliest large-scale projects with a capacity of 125 MW. It is noted for its location in a high-insolation zone and use of crystalline silicon technology.
2. Sakri Solar Plant, Dhule. With a capacity of 125 MW, this plant is part of Maharashtra's diversified renewable energy hub in the northern Dhule district. It is integrated with existing wind farms, forming a hybrid energy cluster that aids in stabilizing grid output.
3. Nanded Solar Park Located in the Marathwada region, this park has a capacity of 130 MW and is significant for its development on drought-prone land, supporting both energy generation and regional economic resilience.

5. RESULT

According to this analysis, India's solar energy development has gone through three different phases: Rajasthan and Gujarat's early dominance, 2014–18, Karnataka's quick rise, 2018–22, and Maharashtra's last years of consolidated growth. State-specific elements, like as geographical dynamics, infrastructure readiness, and solar resource endowment, influence these patterns. This research reveals that solar energy is a nationally promoted priority; its implementation across major Indian states, Karnataka, Tamil Nadu, Maharashtra, Rajasthan, and Gujarat, is profoundly shaped by distinct geographical realities and tailored policy frameworks. Each state has strategically leveraged its unique physical and climatic endowments to advance solar generation, resulting in varied models of development, innovation, and socio-economic integration. Geographically, the resource gradient is decisive. Rajasthan and Gujarat dominate in terms of raw solar potential, with their expansive arid deserts Thar Desert, Rann of Kutch, providing unmatched isolation, 5.8–6.2 kWh/m²/day and vast, contiguous land for ultra-mega parks like Bhadla 2,245 MW and Charanka 790 MW. Their policies thus focus on maximizing scale, attracting private investment through plug-and-play models, and pioneering hybrid projects. In contrast, Karnataka and Maharashtra exhibit a sharp east-west dichotomy due to the rain shadow of the Western Ghats. Their policies, therefore, incentivize development specifically in semi-arid interior plateaus, e.g., Pavagada in Karnataka, Solapur in Maharashtra, and promote innovative land-use solutions, such as Karnataka's land-pooling model and Maharashtra's canal-top solar, to overcome land scarcity. Tamil Nadu, with its coastal-interior divide and strong monsoon influence, has focused on high-capacity projects in its southern arid belt, e.g., Kamuthi, 648 MW, while leveraging its robust grid infrastructure to manage variability. Policy innovation is closely tied to geographic and social constraints. Karnataka's Pavagada Solar Park stands out as a socio-geographic model, transforming low-yield rain-fed land into a community asset through long-term leasing. Gujarat and Rajasthan emphasize geographic co-location, developing hybrid wind-solar-storage parks to smooth intermittency. Maharashtra and Tamil Nadu have increasingly integrated solar with industrial and urban planning, as seen in Dholera Smart City (Gujarat) and Neyveli's mining land repurposing. However, common challenges persist across states, including grid integration, land-acquisition bottlenecks, water scarcity for panel cleaning, and seasonal variability. The states are responding with similar technological shifts: adoption of robotic dry-cleaning, single-axis tracking, and exploration of floating solar on reservoirs. Yet, the pace and focus differ. Rajasthan and Gujarat lead in sheer scale and hybrid projects, while Karnataka and Tamil Nadu excel in distributed generation and inclusive models.

6. CONCLUSION

India's solar energy transition is not a monolithic national project but a mosaic of regionally adapted strategies. The most

successful states are those that have effectively aligned policy incentives with geographical strengths, whether desert expanse, rain-shadow plateaus, or coastal hybrids, while addressing localized socio-environmental constraints. Future policy must continue to encourage this place-based innovation, foster inter-state knowledge transfer on models like land pooling and hybrid systems, and strengthen national grid infrastructure to support the diverse geographic contributions to India's renewable energy future. This geographically nuanced, policy-enabled approach is essential for achieving both national capacity targets and sustainable regional development.

The purpose of this study is to analyze the development trajectory and prevailing trends of solar energy within selected states of India, highlighting its dominant position in the national renewable energy landscape. Among all renewable energy systems, including wind, hydro, biomass, and others, solar power has decisively emerged as the leading source in terms of installed generation capacity. This research examines how geographical, policy-driven, and socio-economic factors across various states have catalyzed solar energy's rapid expansion, enabling it to surpass other renewables and establish itself as the foremost contributor to India's clean energy transition. Through comparative assessment, the study aims to elucidate the strategies and conditions that have positioned solar energy at the forefront of India's renewable capacity, while also evaluating its ongoing challenges and future potential within a diversified renewable portfolio.

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