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Recent Developments and Challenges in Solar Energy Utilization in India

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Abstract: India's shift to renewable energy has sped up significantly over the last ten years. This has made the country one of the leaders in solar power development worldwide. By early 2025, India's installed solar capacity surpassed 75.4 GW, playing a key role in the country's renewable energy mix. This paper offers an analysis of recent technological, economic, and institutional changes in India's solar energy sector. It also examines challenges to large-scale deployment and suggests policy and technical measures to support sustainable growth. Using data from MNRE, IEA, IRENA, and peer-reviewed studies, this research combines trends in capacity growth, regional potential, cost changes, environmental effects, and grid integration challenges. It ends with recommendations to boost domestic manufacturing, improve storage solutions, and strengthen institutional capacity to achieve India's solar targets for 2030.

Keywords: Solar energy, India, renewable energy policy, photovoltaic technology, sustainability, green growth, solar energy utilization.

I. INTRODUCTION

Energy demand in India has grown quickly because of economic growth, urbanization, and changes in population. Access to reliable and affordable electricity is key to social and economic development, but heavy dependence on coal and other fossil fuels has caused environmental and health issues. In response, India has made renewable energy, especially solar power, a major focus in its national energy policy. The Jawaharlal Nehru National Solar Mission (JNNSM) started in 2010, along with many policy tools and incentive programs, has driven large-scale adoption. Additional initiatives like KUSUM and the Production Linked Incentive (PLI) for solar manufacturing aim to increase both installation and domestic production capacity. India enjoys good solar insolation, around 4 to 7 kWh/m²/day in many areas, and has plenty of land available, providing a strong technical resource base. However, challenges related to technology, finance, social issues, and institutions need to be tackled for the long-term growth and sustainability of solar projects. This paper looks at recent developments through 2025, identifies main obstacles, and outlines policy and technical strategies to speed up India's solar transition.

II. LITERATURE REVIEW

Recent scholarship on India's solar transition spans technological innovation, policy design, market dynamics, and environmental assessment. Sharma and Jain (2023) analyze the role of policy stability and financing mechanisms in shaping investor confidence and project outcomes. Gupta and Raj (2024) evaluate hybrid renewable systems, showing how blending solar and wind resources enhances capacity factors and grid stability. Studies by Chaudhary et al. (2023) and Dubey et al. (2024) focus on environmental impacts and end-of-life management, respectively—highlighting the importance of planning for solar waste and recycling. Economists such as Singh and Verma (2024) assess the macroeconomic impacts of solar deployment, including job creation and regional economic development. Technical reviews (Kumar & Bansal, 2023) address advances in photovoltaic materials (perovskites, tandem cells) and system-level improvements including bifacial modules and floating solar. Acrossthe literature, consensus emerges that while cost declines and policy support have propelled growth, persistent challenges—storage, grid integration, land use, and domestic manufacturing—require targeted interventions.

III. METHODOLOGY

This study uses a descriptive-analytical approach based on secondary sources. Data were collatedfrom the Ministry of New and Renewable Energy (MNRE), Central Electricity Authority (CEA), International Renewable Energy Agency (IRENA), International Energy Agency (IEA), and peer-reviewed academic publications covering 2010–2025.

Quantitative indicators analyzed include installed capacity (GW), annual generation (TWh), levelized cost of electricity (LCOE, Rs/kWh), module cost (Rs/W), employment metrics, and estimated CO2 savings. Time series were constructed to illustrate trends, and comparative tables and figures summarize regional potential and cost trajectories. The analysis emphasizes triangulation across multiple sources to ensure robustness.

IV. RESULTS

India's installed solar capacity grew from about 0.2 GW in 2010 to over 75.4 GW by early 2025. This growth happened quickly, especially after 2015, when auction-based procurement and better financing became common. Large-scale solar parks, such as Bhadla and Pavagada, along with distributed installations like rooftop solar and agricultural pumps, both helped drive this growth. Auction prices fell significantly, mirroring global trends in module prices and improvements in efficiency. However, deployment patterns are uneven across the country. Western and southern states, such as Rajasthan, Gujarat, and Tamil Nadu, have a much larger share of big utility-scale projects. In contrast, eastern and some northern states are behind due to weaker policy incentives and issues with the grid. Rooftop solar usage is still low compared to its potential. Institutional barriers and challenges in consumer financing have limited adoption in several urban and peri-urban areas.

V. DISCUSSION

Rapidsolar growth necessitates enhanced grid flexibility. Variability and diurnal cycles create management challenges, especially for regions with high instantaneous solar penetration. Cost- effective storage (battery energy storage systems—BESS), demand response mechanisms, and enhanced transmission capacity are critical. Hybrid projects pairing solar with storage and wind, and seasonal storage solutions (including green hydrogen), are promising pathways to reduce curtailment and improve reliability. Battery technologies—primarily lithium-ion—dominate near-term storage deployments, offering rapid response and modularity. However, lifecycle costs, resource constraints (cobalt, nickel), and recycling challenges necessitate diversified approaches. Pumped hydro remains the lowest-cost large-scale storage option in appropriate geographies but faces site limitations and environmental concerns. Emerging storage options, such as flow batteries and CAES, may become competitive as costs decline.

VI. CHALLENGES

Despite progress, several systemic challenges persist: intermittency and insufficient storage capacity to achieve base-load reliability; supply chain dependence on imports, particularly for critical inputs like polysilicon and cells; financial fragility of DISCOMs impeding timely payments and increasing perceived project risk; grid congestion and inadequate transmission infrastructure in high-potential regions; waste management and recycling of end-of-life solar panels. Addressing these challenges requires coordinated policy action, investment in grid modernization and storage, stronger domestic manufacturing policies, and clear regulatory frameworks for recycling and EPR.

VII. RECOMMENDATIONS

Scale up grid-scale and distributed storage with targeted subsidies and incentives to promote BESS deployment and integration with solar projects; strengthen domestic manufacturing via PLI and R&D grants, while ensuring access to raw materials and technology partnerships; implement DISCOM reforms and financial restructuring to reduce counterparty risk for investors; promote APV, floating solar, and rooftop programs to reduce land-use conflicts and enable decentralized energy access; establish robust EPR frameworks and invest in recycling infrastructure to manage solar e-waste sustainably; encourage blended finance models that combine concessional finance, guarantees, and private capital to reduce cost of capital; support research into next-generation PV technologies (perovskites, tandem cells) and advanced manufacturing to increase efficiency and reduce costs.

VIII. QUANTITATIVE ANALYSIS AND PROJECTIONS

The LCOE is calculated as the ratio of the present value of total costs over lifetime to the present value of electricity generated. For solar, fuel costs are negligible; the main contributors include CAPEX, OPEX, financing costs, and degradation. Sensitivity analysis shows that a 2% increase in discount rate or a 20% CAPEX overrun can raise LCOE materially; conversely, domestic supply chain improvements and lower financing costs can further compress LCOE below Rs.2.0/kWh for utility-scale projects under favorable conditions. Using trend-based modeling and conservative adoption rates, India is projected to reach between 180–240 GW of solar capacity by 2030 under differing policy and finance scenarios. In an ambitious scenario—characterized by rapid domestic manufacturing scale-up, extensive storage deployment, and strong DISCOM reforms—India could reach or exceed the 280 GW target.

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IX. CAPACITY BUILDING AND IMPLEMENTATION

State-level heterogeneity in policy, regulatory capacity, and governance complicates uniform solar deployment. States with proactive policies—subsidies, clear net-metering rules, and streamlined approvals—witness faster rooftop adoption and private investment. Capacity building at the subnational level, involving knowledge transfer, technical assistance, and standardization of permitting processes, would reduce delays and enhance project quality. The expansion of the solar sector has notable socio-economic implications. Job creation spans manufacturing, construction, O&M, and services. Targeted training programs and vocational courses can address the skills gap, ensuring that local communities benefit from employment opportunities.

X. FINANCE, GREEN HYDROGEN AND INTERNATIONAL COLLABORATION

Innovative financing instruments are crucial to bridge the investment gap. Green bonds and yieldco structures can pool project revenues to provide stable returns to investors. Development finance institutions can offer partial risk guarantees, covering political or off-taker risk, which significantly lowers the perceived risk for commercial lenders. Green hydrogen—produced via electrolysis powered by renewable electricity—offers potential for seasonal energy storage and decarbonization of hard-to-electrify sectors. International partnerships can accelerate India's technological capabilities and manufacturing competitiveness.

XI. LIMITATIONS AND FUTURE RESEARCH

This study relies on secondary data, which may have inconsistencies across sources. While triangulation was used, data gaps exist at sub-state levels. Future research should incorporate high-resolution geospatial analysis, techno-conomic modeling of integrated storage and demand response, and empirical studies on social impacts and land-use trade-offs.

XII. ACKNOWLEDGMENT

The author acknowledges the data support provided by the Ministry of New and Renewable Energy (MNRE), International Renewable Energy Agency (IRENA), and the International Energy Agency (IEA). Institutional colleagues who provided feedback during manuscript preparation are gratefully acknowledged.

XIII. CONCLUSION

India's solar sector has seen significant growth due to lower costs, supportive policies, and maturing markets. The mix of utility-scale projects and distributed generation provides a varied path to energy access and reducing carbon emissions. However, to turn technical potential into ongoing progress, integrated strategies are needed.

This includes updating the grid, adding storage, revising manufacturing policy, enacting financial reforms, and ensuring social protections. If policymakers act decisively on the outlined recommendations, India can not only meet but might also exceed its solar targets by 2030, creating environmental, economic, and social benefits.

XIV. FIGURES AND TABLES

Year	Installed Capacity (GW)	Annual Growth (%)
2010	0.2	-
2014	2.6	1200.0%
2018	22	746.2%
2020	40.1	82.3%
2022	59.3	47.9%
2024	72.3	21.9%
2025	75.4	4.3%

State	Estimated Potential (GW)	Installed Capacity (GW)
Rajasthan	280	18.7
Gujarat	250	10.5
Madhya Pradesh	210	7.3
Tamil Nadu	180	6.1

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Uttar Pradesh	160	5

Year	LCOE (Rs/kWh)	Module Cost (Rs/W)
2010	18	18
2015	7	6
2020	3	3
2025	2.3	2.5

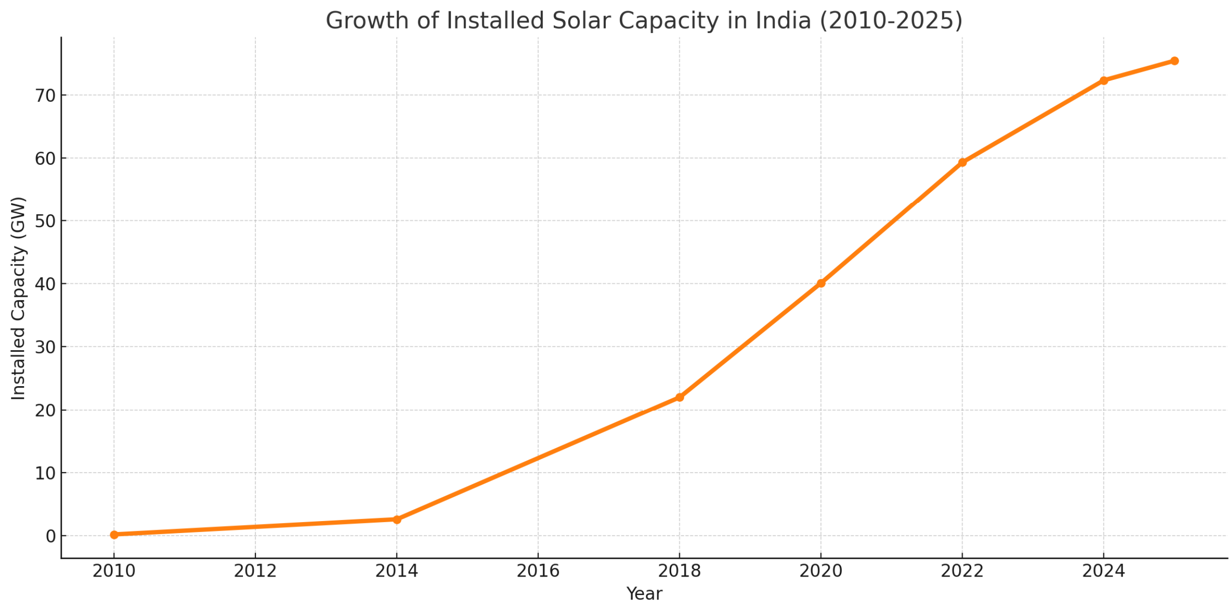

Figure 1: Growth of installed solar capacity in India (2010-2025). Source: MNRE (2025).

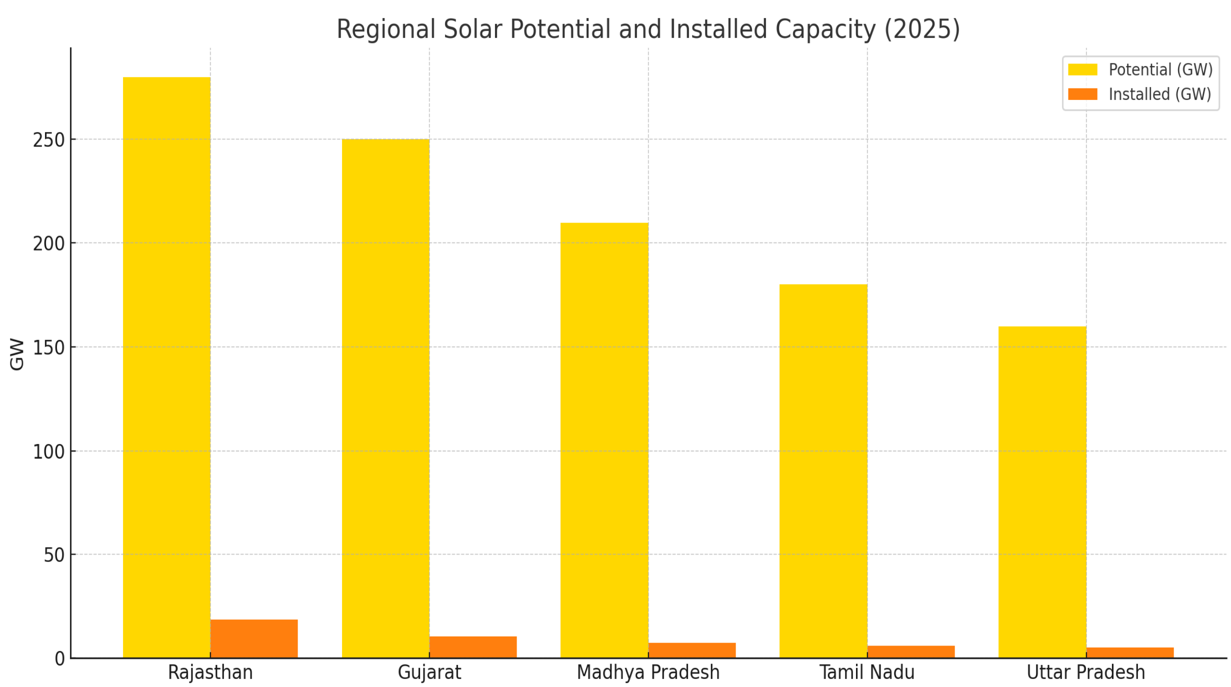

Figure 2: Regional solar potential and installed capacity (2025). Source: MNRE (2025).

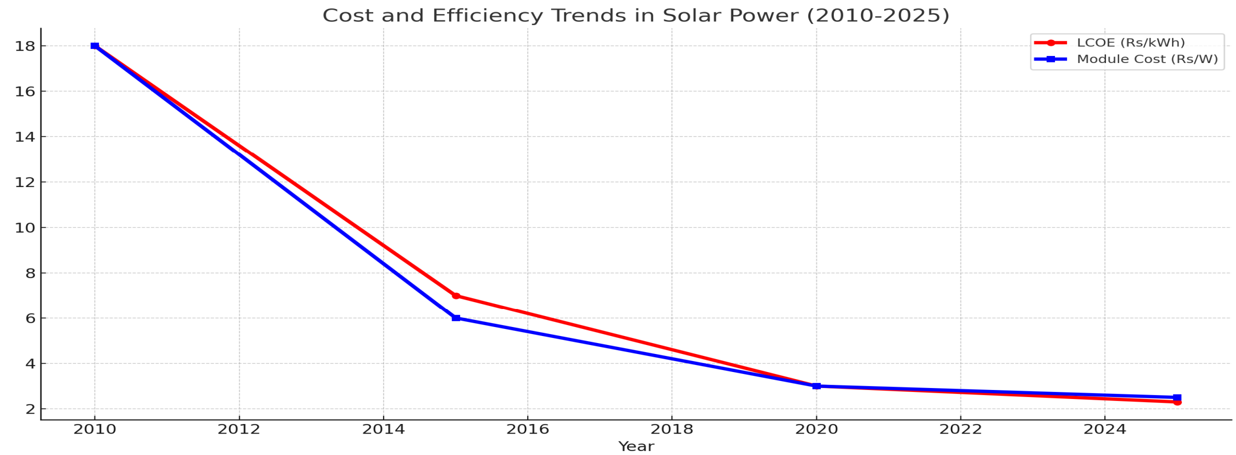

Figure 3: Decline in solar power cost and module costs (2010-2025). Source: IEA (2024).

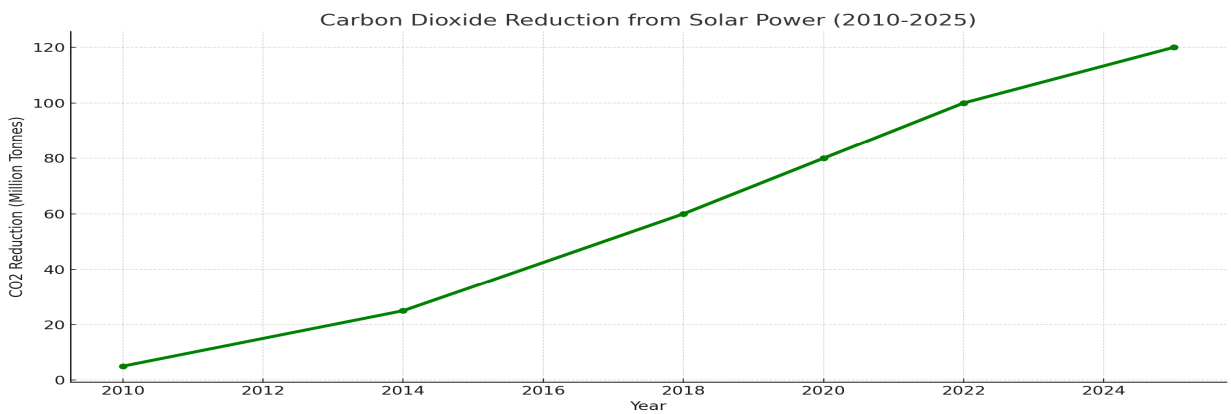

Figure 4: Annual CO2 reduction from solar power generation in India (2010-2025). Source: IRENA (2024).

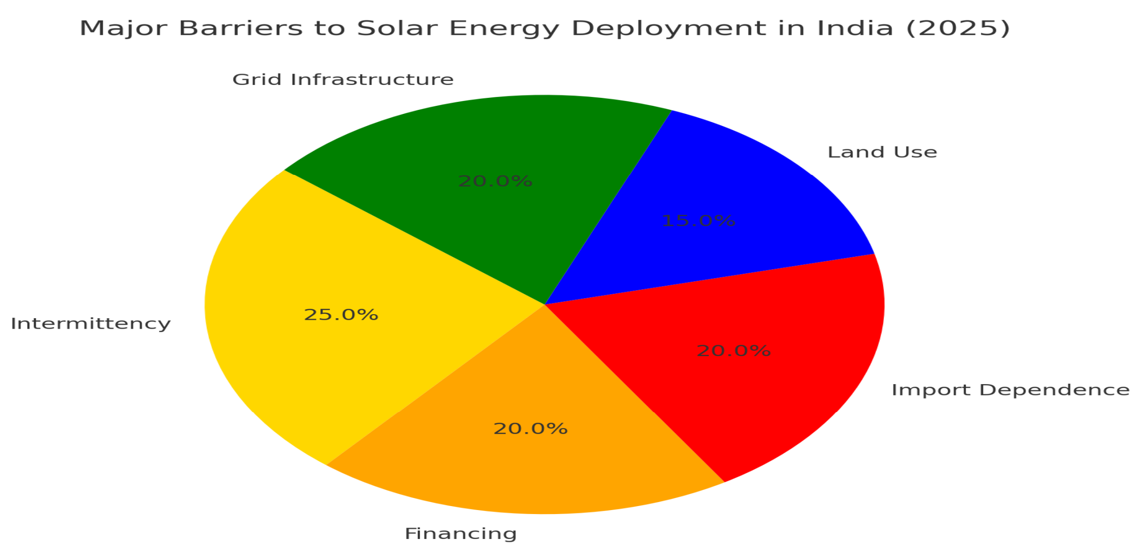

Figure 5: Major barriers to solar energy deployment in India (2025). Source: MNRE (2025).

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