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Research Paper

A Comprehensive Review on the Growth and Development of Solar Energy in India for Sustainable Development

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ABSTRACT

India is at a very critical juncture of its energy transition journey. Solar energy, in fact, has emerged as the major pillar of the country's s sustainable development strategy. This review focuses on the history of policy evolution, technology and future potential of solar energy development in India. The country is now capable of installing solar power generation capacity of over 90 GW, after the officials came up with the National Solar Mission (NSM), PM-KUSUM, Production Linked Incentive (PLI) scheme etc. This paper not only covers foreign solar energy partnerships, grid integration measures, financing instruments, etc. but also comprehensively studies the social and economic impact of solar energy deployment in urban and rural areas. Land acquisition problems, rudimentary grid infrastructure and weak supply chain are the major weaknesses in the solar energy sector, while favourable factors like a fall in PV module prices, green hydrogen introduction and monitoring systems are some of the solar energy development opportunities are discussed. Notwithstanding major achievements, India must have policy consistency, enhanced manufacturing capabilities and rural electrification to meet its renewable energy target of 500 GW by 2030.

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1. INTRODUCTION

Energy security and environmental sustainability have become the major issues of the 21st century. India, being the third largest energy consumer in the world and a population of nearly 1.44 billion people, has to deal with the dual challenge of providing energy to its rapidly increasing population and also meet its international climate commitments under the Paris Agreement (2015). Solar energy, due to its abundant resource potential across the Indian subcontinent, is nowadays considered the ideal solution to these issues. India is blessed with an average solar radiation of 4–7 kWh/m²/day in most of its areas, which is one of the highest solar resource endowments worldwide (Ministry of New and Renewable Energy [MNRE], 2023). This natural strength coupled with the falling prices of photovoltaic (PV) technology and a favourable policy environment, has led to an unmatched solar energy boom in the last 10 years. Starting with an installation capacity of just about 2.6 MW in 2010, India's total installed solar power capacity has crossed 90 GW by early 2025, Because of this making the country the fourth-largest solar market in the world (International Energy Agency [IEA], 2024).

The framework for this change was created through the launch of the National Solar Mission (NSM) by the Government of India in 2010 under the National Action Plan on Climate

Change (NAPCC). There was huge capacity targets set forth in NSM that have been revised multiple times since then. The latest revision of capacity targets is to reach 500 GW of renewable energy capacity by 2030, with the majority of it being solar, which amounts to around 300 GW. This is an illustration of ambition and policy behind India's solar success story (Prime Minister's Council on Climate Change, 2023).

The purpose of this review paper is to systematically analyze the multiple facets of development of solar energy in India. These include policy changes, technology, finance, socio-economic and future issues. The data will be taken from scholarly sources and government and industry reports until 2025.

2. HISTORICAL EVOLUTION OF SOLAR ENERGY POLICY IN INDIA

2.1 Early Foundations (2000–2009)

While India's official interaction with solar power is not linked to NSM, the use of PV technologies in rural electricity, solar water heating systems, and telecommunication facilities from the 1990s to the early 2000s was carried out under the aegis of the Ministry of Non-Conventional Energy Sources (MNES). Later, this ministry became known as the Ministry of New and Renewable Energy (MNRE), and RGGVY initiated in 2005 adopted solar-powered off-grid solutions for un-electrified villages (Tongia & Bhattacharyya, 2021).

The Jawaharlal Nehru National Solar Mission (JNNSM), unveiled in 2009 within the National Action Plan on Climate Change, was the first strategic policy framework entirely devoted to solar energy development. It envisioned a three-phase plan: Phase I (2010–2013) aimed to establish 1,000 MW of solar power connected to the grid, Phase II (2013–2017) 4,000 MW, and Phase III (2017–2022) 20,000 MW – 20 GW in total by 2022.

2.2 Scale-Up and Target Revision (2010–2022)

The decade between 2010 and 2022 saw India's transition from being an insignificant player to a leading power in solar energy. Some important milestones included the following. In 2015, the Indian government increased the target of NSM from 20 GW to 100 GW by 2022, at the same time submitting India's Intended Nationally Determined Contributions for COP21. The five times increase was influenced by technical optimism and geo-political signal regarding India's intentions regarding the role in combating climate change (Chaturvedi et al., 2022).

It is worth noting that the Ultra Mega Solar Power Projects (UMSP), Solar Parks policy, and Viability Gap Funding (VGF) have been crucial in attracting large investments in the sector. With solar parks in Rajasthan, Gujarat, and Andhra Pradesh being plug-and-play projects, the risk level in developing such projects has been considerably decreased. In addition, the Bhadla Solar Park, which is supposed to generate 2,245 MW in Rajasthan, has become the world's second-largest solar park (SECI, 2023).

With India crossing the mark of 100 GW installed renewables power in 2021, where the share of solar amounted to about 45 GW (being lower than the 100 GW target for solar, but still showing a 1,700-fold growth compared to 2010 figures), the gap could be explained by the issues in grid connectivity, land acquisition process, and the COVID-19 impact (MNRE, 2022).

2.3 Post-2022 Acceleration and the 500 GW Vision

This post-2022 era can be described by an even more aggressive solar plan based on the updated NDC goal of having a capacity of 500 GW of electricity generated by non-fossil fuel resources by 2030. As per 2025, the solar power capacity installed in India is above 90 GW, which shows that there is a well-planned pipeline of projects in progress. The Production Linked Incentive Scheme of the Indian Government for making solar PV in the country is worth INR 24,000 crore and intends to develop 10 GW integrated solar manufacturing capacity in India, cutting dependency on Chinese modules and cells (DPIIT, 2023).

3. POLICY AND REGULATORY FRAMEWORK

3.1 National Solar Mission and Associated Programs

The hierarchy of policies that exist within the Indian solar energy sector include a multi-tiered approach from central to state governments and to local governments. Within the hierarchy at the central government level, the NSM continues to be the main structure, supplemented by several other subordinated schemes. The Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) program, which was introduced in 2019, seeks to focus on the agriculture sector by setting a goal to create 10,000 MW of decentralized solar power plants using barren or fallow lands (component A), solar power pumps (component B) for 1.5 million grid connected agriculture, and solar power pumps (component C) for 2.5 million non-grid agriculture pumps. By 2024, more than 300,000 pumps were solarized under PM-KUSUM (MNRE, 2024a).

3.2 International Solar Alliance

The leadership role played by India in the International Solar Alliance (ISA) since its formation in 2015 at COP21 alongside France and the operation of the body in 2017 has made the country emerge as a world leader in championing solar energy for development in sunny countries. With the membership of 124 countries in 2025, the ISA has helped foster technology exchange programs that have been of benefit to India's solar players in the industry (ISA Secretariat, 2024).

3.3 State-Level Policies

The state governments, on the other hand, have acted as important complements to the development of the industry through net metering laws, wheeling and banking, renewable purchase obligation (RPOs), and solar policies in the states. Rajasthan, Gujarat, Maharashtra, Tamil Nadu, and Karnataka have become important states for solar energy production, accounting for more than 60% of all installations. The Gujarat Solar Policy of 2009, which established the first feed-in tariff for solar in India, offered an example for others to follow (Patel & Desai, 2023).

4. TECHNOLOGICAL ADVANCEMENTS IN INDIAN SOLAR SECTOR

4.1 Photovoltaic Technology Trends

In India, the most used solar technology has been c-Si (crystalline silicon) PVs, including monocrystalline and polycrystalline technologies. Rapid increase in cell efficiency (15% for common polycrystalline modules in 2010 to more than 22% for monocrystalline PERC [Passivated Emitter Rear Contact] modules in 2024) has led to a substantial increase in generated power per area unit thus decreasing the footprint of the land needed for the installation of solar panels (Sharma & Meena, 2024).

Use of bifacial solar modules that produce energy on their front and rear sides has become increasingly popular in large scale utility projects in Indian deserts that feature high albedo ground surfaces. According to industry statistics, use of such modules allows generating up to 8-15% extra energy compared to monofacial modules in Indian conditions (Bharat Solar Energy, 2023). Development of n-type TOPCon (Tunnel Oxide Passivated Contact) cells with 24% efficiency has become the next step of efficiency increase and will be implemented in India starting from 2024.

4.2 Solar-Storage Integration

The adoption of battery energy storage systems (BESS) technology for solar generation is now recognized as a vital technological frontier as it provides solutions to intermittent nature of solar energy. The RTC (round the clock) bids tendered for renewable energy production from 2019 by SECI mandated the tender bidders to incorporate storage or hydro energy with solar power for provision of assured power generation. In 2024, several RTC solar projects with integrated pumped hydro and large-scale lithium-ion batteries were under development with a total of 2 GW (CEA, 2024).

4.3 Green Hydrogen and Solar Synergies

The National Green Hydrogen Mission of India, unveiled in January 2023, aims at an annual production capacity of 5 million metric tons of green hydrogen by 2030, mostly based on solar power through electrolysis. This is a paradigm-shifting use of solar energy that goes beyond the traditional use for power generation and will allow de-carbonization of difficult to abate sectors such as fertilizer plants, steel manufacturing, and heavy industries. Some pilot projects have already been started with the placement of electrolyzers alongside solar installations in Rajasthan and Gujarat from 2023 to 2025 (Ministry of New and Renewable Energy, 2024b).

5. ECONOMIC AND FINANCIAL DIMENSIONS

5.1 Cost Trajectory and Tariff Evolution

The reduction in solar tariffs could arguably be one of the best metrics to showcase India's solar revolution. The solar PPAs of India during the years 2010–11 was executed at INR 17–18/kWh. However, by 2023–24, through solar auctions in the state of Rajasthan, tariffs had declined to INR 2.15–2.20/kWh, resulting in a reduction of 87% in tariff terms and even more in real terms (Mercom India, 2024). The above cost reduction is attributable to the combination of declining prices of global polysilicon, scale advantages of module manufacturing, and competitive bidding processes.

5.2 Investment Flows

Foreign direct investment in renewable energy reached US $12.4 billion in fiscal year 2023-2024, with solar accounting for around 75 percent of the total, ranking India among the top five countries globally in terms of solar investment attraction (BloombergNEF, 2024). Such investments have been supported by stable policies in this area, an increasingly favorable environment for doing business, and the well-developed financing market in India in terms of infrastructure projects. Some of the companies investing in the solar industry in India are industrial groups like Adani Green Energy, Tata Power Renewables, Greenko, along with international companies specializing in renewable energy like Total Energies, ACME Solar, and ReNew Energy.

5.3 Financing Mechanisms

Solar power projects in India have seen a transition from mostly domestic loans to an ecosystem of green bonds, Infrastructure Investment Trusts (InvITs), Overseas Development Finance (from entities like KfW, ADB, World Bank, US DFC), and project finance syndications. The Solar Energy Corporation of India (SECI), which is a Government of India undertaking, acts as a key intermediary in solar energy auctions, ensuring safety arrangements that help minimize counterparty risks when developers enter into business with poorly performing state electricity distribution utilities (DISCOMs).

6. SOCIO-ECONOMIC AND ENVIRONMENTAL IMPACTS

6.1 Rural Electrification and Energy Access

Solar power has been instrumental in providing energy to the remote and rural parts of India. The Pradhan Mantri Sahaj Bijli Har Ghar Yojana or Saubhagya scheme was introduced in 2017 and has made near-universal electrification of the population possible by 2019 through solar standalone systems and mini-grids which cater to about 2.8 million households in those regions where grid expansion was not feasible during the implementation period (Ministry of Power, 2023). Solar home systems, lanterns, and solar power generation in communities has led to improved livelihoods, extended studying hours for children, and entrepreneurial initiatives in villages using kerosene and diesel until now.

6.2 Employment Generation

Solar energy industry has become themajor employment vehicle, both direct and indirect, with approximately 1. 2 million people involved in various segments such as manufacturing installation operations and maintenance, and project development by 2024 (CEEW, 2024). The focus on domestic solar production under the PLI scheme and Atmanirbhar Bharati initiatives will Much boost job opportunities in manufacturing sector, with estimates of around 500,000 more jobs being created if the 30 GW capacity target under PLI is achieved.

6.3 Environmental Co-Benefits

Solar energy deployment in India has played an important role in enabling the electricity sector's decarbonization. Through 2024, the total CO2 emissions that have been avoided by using solar energy are expected to be around 180 million tonnes, which is the same as removing 39 million passenger vehicles from the roads for one year (MNRE, 2024c). On top of that, solar energy deployment has resulted in lowered local air pollution by replacing coal-based generation, with particulate matter (PM2. 5) and sulfur dioxide (SO2) being Mainly high in coal-based states.

7. CHALLENGES AND BARRIERS

7.1 Grid Integration and Curtailment

With the increasing penetration level of solar power, the issue of grid integration has become one of the most critical challenges. The intermittency in the generation of power from solar sources, which is usually higher in the midday hours and non-existent in nighttime, has resulted in time mismatches between supply and demand and pressure on the transmission system. With respect to states with high penetration levels of solar energy such as Rajasthan and Tamil Nadu, cases of curtailment of solar power have increased during off-peak hours (CEA, 2024).

7.2 Land Acquisition

Land acquisition continues to be one of the most enduring constraints in the development of utility-scale solar projects in India. The fact that 4-5 acres of land is required for each MW of solar capacity, coupled with the fragmented nature of land holding, differential state policies, and social concerns over conversion of agricultural land to solar land, has resulted in many projects being held up. The creation of solar parks through the use of government-owned waste lands has helped overcome some of the hurdles, though the availability of waste land in adequate quantity is limited (Jain et al., 2023).

7.3 Manufacturing and Supply Chain

India's domestic ecosystem of solar panel production is still in its infancy stage compared to the scale of implementation, with domestic production capacity for solar panels estimated at around 40 GW per year by early 2025, while indigenous production capacity for cells and wafers is extremely limited. This high dependency on solar cells and wafers imported into the country, especially from China, makes India vulnerable to any changes in trade policies, geopolitical developments, and fluctuations in currency rates. Duties on imported solar modules and cells, levied from 2022 to encourage domestic production, had a temporary impact on project costs (MNRE, 2024d).

7.4 DISCOM Financial Health

Distribution companies (DISCOMs), who constitute the major buyers of solar power in India, suffer from financial frailty due to the overall loss amounting to INR 3.5 lakh crore as of 2023. The financial instability results in delayed payments and default in solar power purchase agreements, making the transaction risky for solar power producers and driving up the cost of finance for solar projects. Without any reforms in DISCOMs that entail efficient tariffs, AT&C losses and operation optimization, the sustainability of solar sector in India is under threat (ICRA, 2024).

8. FUTURE OUTLOOK AND RECOMMENDATIONS

8.1 Pathways to 500 GW by 2030

Meeting India's renewable energy targets of 500 GW of renewable energy by 2030, including about 300 GW from solar energy, would involve setting up at least 20 GW of new solar energy capacity every year till 2030, beginning with 2025, which is a steep rise from the 15 GW of solar energy installed in 2023-24. Technically, this is possible but requires solving the grid constraints, land availability and finance issues highlighted in this paper. The scenarios have suggested a mix of utility-scale solar parks, rooftop solar, agrivoltaics and floating solar on waterbodies to achieve this without causing land use issues (NITI Aayog, 2023).

8.2 Emerging Technologies and Innovation

There are several innovative technological advances that could help transform India’s solar sector. Agrivoltaic systems, involving the placement of solar panels above agricultural farms, have been gaining much attention in research and development given the dual challenges of availability of solar land and water stress on Indian agriculture – early experiments suggest that agrivoltaics could help decrease crop water needs by 20-40%, simultaneously producing solar power on the same piece of land. India’s enormous irrigation reservoirs, hydropower reservoirs, and other bodies of water present yet another possibility for landless solar generation, with an estimate of over 280 GW of technical potential (National Institute of Solar Energy, 2023).

8.3 Policy Recommendations

As observed from the detailed literature review, there are several policy recommendations that arise as being critical for further development of solar energy sector in India. First of all, it is crucial to ensure more rapid development of the transmission infrastructure according to the schedules of increase in solar capacity in close cooperation between MNRE, the Ministry of Power, and PGCIL. Second, it is important to implement battery storage hybridization through the mandatory tender process when designing new utility-scale solar plants as the share of solar energy generation increases. Third, creation of dedicated solar manufacturing zones with favorable infrastructure conditions, workforce education programs, and R&D activities becomes a must for promoting local manufacturing within the PLI program and subsequent industrial policy strategies. Finally, comprehensive DISCOM reform, which involves tariff adjustments, mass-scale introduction of smart meters, and other actions increasing efficiency and financial stability of the company, must accompany the development of renewable energy generation.

9. CONCLUSION

The Indian solar energy story is among the most remarkable examples of energy transition in recent times, taking the country from virtually zero capacity in installed solar generation to become a global leader in just fifteen years. This impressive feat has been enabled by rich solar resources, government incentives, falling costs of technology, and foreign investments that have helped the country install almost 90 GW of solar generation capacity by early 2025. Therefore, solar energy plays a critical role in India's approach to sustainable development, energy security, and climate mitigation. Nevertheless, future growth faces more complex challenges. Meeting the challenging goal of installing 500 GW of renewable energy capacity by 2030 without compromising the stability of the grid system, broadening access to electricity, enhancing domestic solar manufacturing capabilities, guaranteeing environmental sustainability, and addressing the financial situation of DISCOMs requires coordinated policy-making, institutional cooperation, and investment by both the public and the private sectors. There are several obstacles to the expansion of solar capacity, including poor transmission infrastructure, difficulties in acquiring land, stressed finances of DISCOMs, and heavy dependence on imported solar parts. Overcoming these problems is essential not only for the Indian developmental process but also for other developing nations.

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