Growth and Economic Impact of Solar Energy in India

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Abstract: **India, endowed with abundant solar radiation, has emerged as one of the global leaders in solar energy development. India has enormous potential for solar energy. India's land area receives about 5,000 trillion kWh of energy annually, with the majority of its regions receiving 4–7 kWh per square meter per day. Volatility in power supplies is a problem for the Indian power industry. India's primary energy source is coal, which is not a sustainable long-term solution. Therefore, renewable energy is the way of the future for India's energy supply, and solar energy is the most well-known and dependable renewable energy source. With ambitious renewable energy targets, favourable government policies, and significant investment in solar infrastructure, India is poised to leverage its solar potential for sustainable growth. This paper explores the growth trajectory, economic opportunities, challenges, and future potential of solar energy in India, focusing on its role in energy security, job creation, and climate change mitigation.**

Keywords: **renewable energy, government policies, economic opportunities, Solar energy.**

1. INTRODUCTION

Since ancient times, people have revered the Sun as the source of life on Earth. We learned about sunlight as an energy source during the industrial era. India has enormous potential for solar energy. Solar energy is generated when sunlight is converted into electricity. Photons are light energy units that make up sunlight. When sunlight strikes the earth, solar panels may absorb the energy and convert it into electrical energy that can be used. Solar panels use photovoltaic cells to capture photons from sunshine and transform them into electrical energy. After that, the electricity is sent to an inverter, which powers residences and commercial buildings. Solar panels are typically placed on rooftops or the ground for optimal exposure to the sun's rays. They can be installed on small businesses and individual residences, as well as in large-scale commercial installations that typically occupy a sizable amount of land. In any scenario, each solar panel is connected to a grid or battery system that can store excess energy for further use. While all renewable energy sectors have been growing, the solar energy sector has experienced particularly rapid expansion. Over the last ten years, solar energy has grown at an average annual rate of 33%, making it the world's fastest-growing source of electricity. This trend is predicted to continue. Numerous variables contribute to this growth rate. First, the price of solar panels has been falling significantly, making solar energy investments more affordable for both businesses and households. Second, solar energy has become a more appealing source of electricity due to government regulations and incentives like tax credits and renewable energy standards. Last but not least, changing consumer tastes have caused many to choose clean renewable energy sources like solar over more polluting ones.

India's land area receives about 5,000 trillion kWh of energy annually, with the majority of its regions receiving 4–7 kWh per square meter per day. In India, solar photovoltaic power can be used efficiently and scaled up significantly. Additionally, solar allows for distributed power generation and allows for quick capacity additions with short lead times. In addition to satisfying other energy demands for power, heating, and cooling in both rural and urban areas, off-grid decentralized and low-temperature applications will be beneficial from the standpoint of rural applications.

2. REVIEW OF LITERATURE

Festus (2016): This paper provides a technical review of solar energy stand-alone and hybrid installations, taking into account the various practical issues that arise during installation and operation. The preferred solutions are discussed, with a focus on domestic and industrial installations. They came to the conclusion that independent energy supply to the hybrid device helps prevent total or complete breakdown that could result in a single blackout. *Seh (2018):* Explored the use of solar-driven electrolysis for hydrogen production, showcasing its potential for long-duration energy storage. *Frischknecht (2018):* Conducted a life cycle assessment of crystalline silicon PV panels, finding a significant reduction in

carbon emissions compared to fossil fuels. *Singh et al. (2019)* Explored thermal storage solutions for Concentrated Solar Power (CSP) plants in Rajasthan, highlighting improved energy dispatch reliability. *Jakubiec and Reinhart (2019)*: Modeled urban rooftop solar potential in dense city environments, emphasizing design optimization to maximize energy generation. *Barbose . (2020)*: Analyzed the effectiveness of government incentives in driving solar energy adoption in the United States. Findings indicated a strong correlation between subsidies and increased installation rates. *Zhang (2020)*: Evaluated the thermal efficiency of CSP plants using molten salt as a storage medium. Results demonstrated increased efficiency with improved heat transfer fluids. *Agarwal (2020)*: Focused on the development of cost-effective thin-film solar cells using indigenous materials to reduce reliance on imports. *King (2021)*: Focused on multi-junction solar cells for space applications, achieving record efficiencies of over 40%. *Mathur(2021)*: Evaluated the feasibility of using lithium-ion batteries in Indian solar projects. Challenges included high import costs and the need for local manufacturing of battery components. *Alsema . (2021)*: Evaluated the cost-benefit analysis of implementing solar systems in off-grid rural areas. Findings indicated substantial economic and social benefits despite initial costs. *Chatterjee (2021)*: Compared state-level solar energy policies in Gujarat and Karnataka, showing how incentives like net metering significantly boosted rooftop solar adoption. *Shrestha (2021)*: Reviewed AI applications in predicting solar irradiance and optimizing energy generation. Highlighted deep learning algorithms for enhancing system performance. *Bhattacharya (2021)*: Highlighted issues such as financing, grid integration, and policy inconsistency as key barriers to solar adoption in India. *Yang (2022)*: Explored the use of perovskite materials in solar cells, achieving efficiencies exceeding 25%. The study highlighted the importance of stability and scalability for commercial adoption.

3. OBJECTIVES AND RESEARCH METHODOLOGY

This study is conducted to full fill the following objectives:

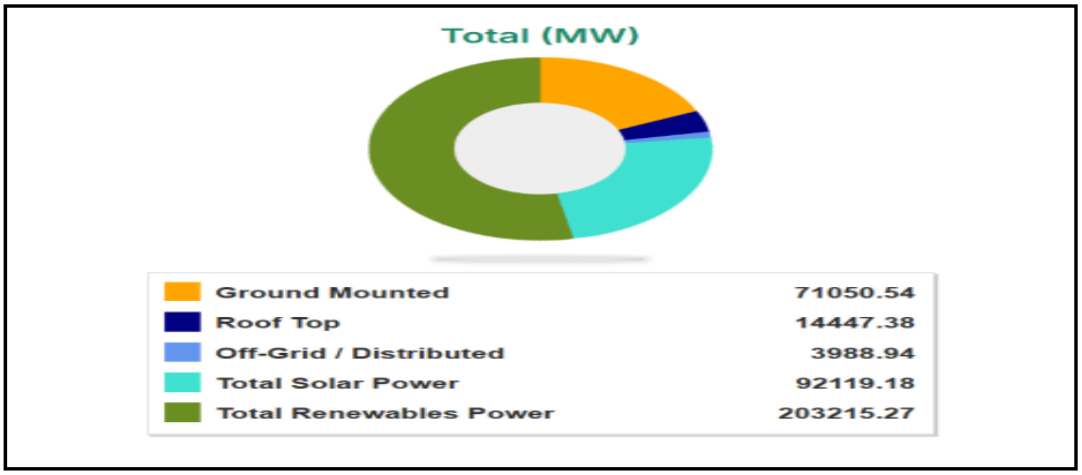
- To overview the current scenario of Solar energy in India
- To study the Economic Effects of Solar Power in India
- To identify the Challenges in Scaling Solar Energy
- To find the Future Prospects of Solar Energy in India

This research paper has been carried out in the Indian context using only secondary sources of data, to provide a comprehensive, evidence-based analysis of the Impact, Challenges and future Prospects of solar energy in India. A variety of published reports and articles, including newspaper stories, journal articles, magazines, research articles, periodicals, website and policy papers, have been utilized to conduct the semi-systematic evaluation.

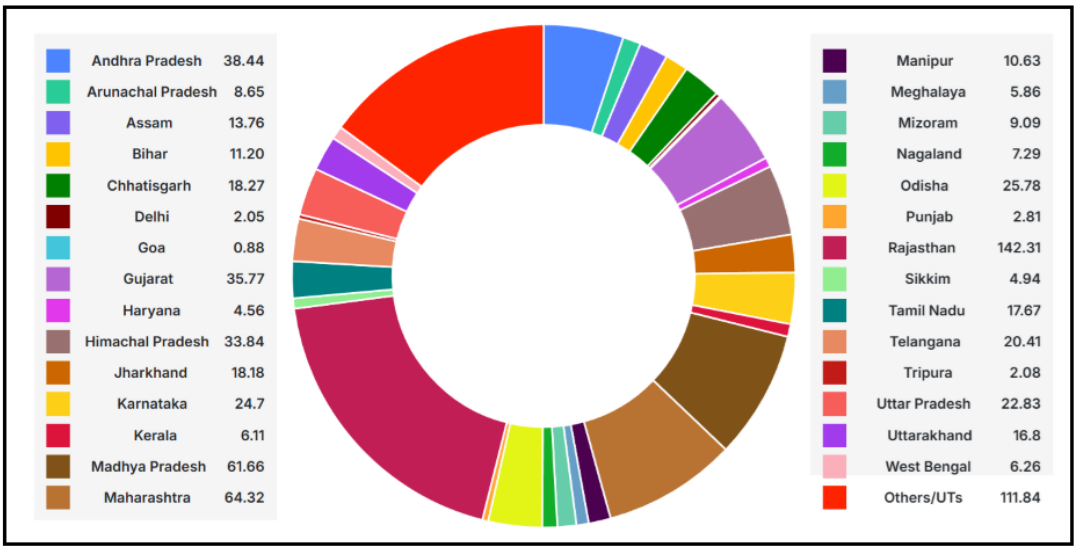
4. GROWTH AND CURRENT STATUS OF SOLAR ENERGY IN INDIA

India is one of the leading countries in solar energy adoption, driven by ambitious government targets, technological advancements, and an increased focus on renewable energy. Growth in Solar Capacity:
2001–2010: The growth of solar energy in India during this period was relatively slow, with limited adoption due to high costs and lack of infrastructure.
2010–2024: The launch of the National Solar Mission in 2010 marked a turning point. With ambitious targets and policy support, solar capacity increased from around 18 MW in 2010 to over 92 GW by 2024, making India one of the largest solar markets globally. The solar energy sector in India has witnessed remarkable growth and transformation. India has an installed solar energy capacity of over 70 GW, making it the fourth-largest solar power producer globally. Breakdown of Capacity:
Utility-Scale Solar Projects: ~73 GW
Rooftop Solar Projects: ~14GW
Off-Grid Solar Systems: ~5 GW

1. Total installed capacity of Grid/ Off-Grid Interactive Renewable Power.
(as on 30.06.2023)



2. State-wise estimated Solar Energy Potential in the Country (Gwp)



Source: NSEFI

4.1 Contribution to Energy Mix: Solar energy accounts for approximately 15% of India's total renewable energy capacity, which is around 175 GW. Renewable energy, including solar, contributes about 25% to India's total electricity generation.

4.2. Geographic Distribution

Top States of India in Solar Capacity are: Rajasthan: ~16 GW (Leading state with the largest solar park, Bhadla Solar Park), Gujarat: ~10 GW (Known for its decentralized solar projects), Karnataka: ~8 GW,Tamil Nadu and Andhra Pradesh: Significant contributors to solar capacity. India receives abundant solar radiation, with an average of 4-7 kWh/m²/day, making most regions ideal for solar power generation.

4.3 Government Initiatives and Schemes:

To promote solar power generation in the nation, the Indian government has introduced a number of programs, including the Solar Park Scheme, VGF Schemes, CPSU Scheme, Defence Scheme, Canal Bank & Canal Top Scheme, Bundling Scheme, Grid Connected Solar Rooftop Scheme. The government has taken a number of actions to encourage the use of solar energy in the nation. These consist of:

- Allowing 100% of foreign direct investment (FDI) through the automated process, Interstate transmission system (ISTS) fees are waived for solar and wind energy sales across states for projects that are scheduled to be put into service by June 30, 2025.
- An announcement of the Renewable Purchase Obligation's (RPO) trajectory through 2029–2030
- Declaration of trajectory for Renewable Purchase Obligation (RPO) up to the year 2029-30,
- Notification of standards for deployment of solar photovoltaic system/devices,

- Setting up of Project Development Cell for attracting and facilitating investments,
- Standard Bidding Guidelines for tariff based competitive bidding process for procurement of Power from Grid Connected Solar PV and Wind Projects.
- Government has issued orders that power shall be dispatched against Letter of Credit (LC) or advance payment to ensure timely payment by distribution licensees to RE generators.
- Notification of Promoting Renewable Energy through Green Energy Open Access Rules 2022.
- Notification of "The electricity (Late Payment Surcharge and related matters) Rules 2002 (LPS rules).
- Launch of Green Term Ahead Market (GTAM) to facilitate sale of Renewable Energy power including Solar power through exchanges.

National Solar Mission:
Jawaharlal Nehru National Solar Mission, launched in 2010, which aims to achieve 100 GW of solar power capacity by 2022. This ambitious target has spurred significant growth in the solar sector, attracting both domestic and international investments. The solar industry has grown significantly as a result of this ambitious goal, which has drawn both domestic and foreign investment. Many people find solar energy to be a financially realistic choice because the government also provides tax breaks and subsidies to promote its use. These programs have been crucial in propelling the nation's broad solar power adoption and have helped India emerge as a global leader in renewable energy.

Solar Park Scheme: Its designed to establish 50 Solar Parks of 500 MW and above with a cumulative capacity of ~38 GW by 2025-26. These solar parks act as hubs for solar energy generation, attracting investments and fostering a conducive environment for solar power development. They are instrumental in achieving economies of scale, making solar energy more affordable and accessible. Under this scheme, so far, 11 Solar Parks with an aggregate capacity of 8521 MW have been completed, and 7 Solar Parks with an aggregate capacity of 3985 MW have been partially completed. In these parks, solar projects of an aggregate capacity of 10,237 MW have been developed.

International Solar Alliance (ISA): which was established in 2015 by the President of France and the Hon. Prime Minister of India. It is a cooperative, member-centred platform that is action-oriented and aims to generate 450 GW of renewable energy by 2030. By increasing energy access, guaranteeing energy security, and accelerating the energy transition among its member nations, it seeks to improve the broad adoption of solar energy technologies.

PLI Scheme for Solar Manufacturing:
The Production-Linked Incentive (PLI) scheme aims to boost domestic manufacturing of solar PV modules and reduce dependency on imports.

PM-KUSUM Scheme:
The goal of this program is to give farmers the finan cial and technical assistance they need to establish s olar power plants on their arable or bare land to increase farmers' incomes, minimize reliance on conventional fossil fuels, and provide a dependable power source for irrigation.

Rooftop Solar Subsidy Program:
The Solar Rooftop Scheme is a pioneering initiative aimed at promoting the widespread adoption of solar energy by harnessing rooftop spaces for power generation. Under this scheme, residential, commercial, and industrial consumers are encouraged to install solar panels on their rooftops to generate electricity for their own consumption.

5. BENEFITS OF SOLAR ENERGY

Solar energy offers numerous benefits, making it a popular choice for sustainable energy production. Here are some key advantages:

- Solar energy is derived from the sun, an inexhaustible and abundant resource, unlike fossil fuels which are finite.
- Solar energy production generates minimal greenhouse gases and air pollutants, reducing carbon footprints and combating climate change.
- It doesn't produce water or noise pollution.
- Once installed, solar panels significantly reduce electricity bills since sunlight is free.
- Governments often offer incentives, tax breaks, and rebates for solar installations, making it more affordable.
- Solar power allows individuals and nations to reduce reliance on imported fuels, enhancing energy security.
- Homeowners with solar panels can generate their own electricity, becoming less dependent on utility companies.

- Solar panels require minimal maintenance and have long lifespans (typically 25–30 years).
- There is no recurring fuel costs associated with solar energy systems.
- Solar energy can be used in various applications, including generating electricity (via photovoltaic cells) and heating (solar thermal systems).
- It can power small-scale systems like calculators or large-scale systems like power plants.
- The solar industry creates jobs in manufacturing, installation, maintenance, and research and development.
- Solar energy can bring electricity to remote or rural areas where traditional grid access is unavailable.
- Portable solar devices can provide power in emergencies or off-grid locations.
- Solar systems can be customized to meet different energy demands, from small residential setups to large commercial installations.
- Distributed solar installations (rooftop systems) reduce the strain on centralized power grids and lower the risk of blackouts.
- Ongoing research is improving solar panel efficiency, storage solutions, and integration into smart energy systems, making solar energy even more attractive.

Solar energy represents a clean, sustainable, and economically beneficial energy solution, contributing significantly to a greener future.

6. ECONOMIC IMPACT OF SOLAR POWER IN INDIA

The solar sector has become an increasingly significant contributor to India's GDP, particularly over the past two decades (2001–2024), as the country has prioritized renewable energy to meet its energy needs, enhance energy security, and reduce greenhouse gas emissions.

6.1 The Solar Power Horizon in India

With ambitious goals for solar energy, India's National Solar Mission plans to generate 100 GW of solar power by 2022 and plan to further expand in the years that follow. By 2023, India's installed solar capacity had surpassed 70 GW, significantly enhancing its renewable energy status. As a result of its quick growth, India is now among the world's leading nations, giving the actively operating solar power enterprises a tangible platform.

6.2 Generation of Employment opportunities:

Large-scale employment possibilities are subsequently generated by solar power projects at various phases of the manufacturing/installation, operation, and maintenance of facilities associated with solar energy. Since the demand for such installations has increased in the areas around the country, the number of individuals needed for that work, primarily in electrical engineering, construction, management, and maintenance, has skyrocketed. Employment in rural areas, especially concerning large-scale solar installations, is booming, and the money stays in the community. Solar power companies also promote indirect employment through the supply chain, transport, equipment manufacture, and material acquisition. As the solar power industry expands, so does the need for adjacent sectors, creating an ecosystem that encourages sustainable growth.

6.3 Infrastructure Development:

Rural Electrification: This is one of the biggest benefits of solar power projects in India. The national electrical grid is not easily accessible in many Indian villages, especially in states like Rajasthan, Bihar, and Uttar Pradesh. In some places, off-grid solar solutions, such as solar lights and home systems, have significantly raised living standards. Because they supply clean, dependable energy, commercial businesses, hospitals, and schools can operate effectively.

Industry Growth: As the number of solar projects increases, so do related industries including the production of solar panels, inverters, and battery storage. This encourages future industrial development and backs initiatives to strengthen Made in India.

6.4 Investment Inflows: Solar projects attracted significant domestic and foreign investments, with billions of dollars flowing into solar parks, rooftop installations, and manufacturing facilities for solar panels and related technologies.

6.5 Reduced Energy Imports: By increasing solar energy production, India reduced its dependency on fossil fuel imports, positively impacting the trade deficit and strengthening the economy.

6.6 Increases Property Value: Homes equipped with solar panels often have higher resale values due to lower energy costs and growing demand for eco-friendly properties.

7. CHALLENGES IN SCALING SOLAR ENERGY

7.1. Land Acquisition and Infrastructure: Extremely large-scale solar farms require huge areas of land, with a consequence being significant costs in areas where land is costly or highly sought after for agricultural or housing purposes. Large-scale solar farms require extensive land, often conflicting with agricultural and environmental interests. Infrastructure constraints, such as grid integration and energy storage, pose challenges to scalability.

7.2. Financial Barriers: High upfront costs for solar projects, especially for residential and small-scale users, hinder adoption. Limited access to financing for developers and consumers remains a bottleneck.

7.3. Policy and Regulatory Hurdles: Complex regulatory frameworks and inconsistent policies across states affect project implementation. Delays in approvals and land clearance reduce the pace of solar energy deployment.

7.4. Technology and Efficiency Issues: Solar PV modules' efficiency can decline due to India's climatic conditions (e.g., dust, high temperatures). Dependence on imports for key components like solar cells and modules limits domestic innovation.

7.5 High Cost of Solar Energy Investment: High initial capital costs are one of the major hurdles against the growth of solar energy is the expensive cost involved in installing it. Solar power plants, more so mega-scale solar farms, require significant investments like

- Solar Panels
- Balance of System
- Inverter units
- Lot of Space

7.6 Storage of energy costs: Electricity storage technologies (such as batteries) are required to maintain a steady supply of electricity, particularly on cloudy days or at night. However, the cost of effective, large-scale energy storage options remains quite expensive.

7.7 Grid Integration Costs: Integration of the current electric system with solar power would present logistical and economic challenges. It will require more such infrastructure, like grid stabilization devices and smart grid technology, to smooth out the unpredictable and intermittent nature of solar energy. These infrastructure renovations and expansions carry a high price tag, especially for utilities and governments.

8. FUTURE PROSPECTS OF SOLAR ENERGY IN INDIA

8.1. Technological Innovations- Advancements in solar panel efficiency, energy storage (batteries), and hybrid systems (solar-wind) can boost adoption. The integration of artificial intelligence (AI) and the Internet of Things (IoT) in solar systems can optimize energy production and consumption.

8.2. Rooftop Solar Growth- Rooftop solar projects are expected to grow with supportive government schemes like subsidies and net metering policies. Increasing awareness and decreasing costs will drive residential and commercial adoption.

8.3. Solar Parks and Large-Scale Projects- Development of ultra-mega solar parks (e.g., Bhadla Solar Park) can enhance large-scale power generation capacity. International collaborations and investments will play a key role in scaling such projects.

8.4. Export Potential- India's growing manufacturing capabilities can position it as a global hub for solar panels, inverters, and other components. Participation in global renewable energy supply chains can boost exports.

8.5. Climate Goals and International Leadership- Solar energy will be pivotal in achieving India's renewable energy target of 500 GW by 2030. India's leadership in the International Solar Alliance (ISA) strengthens its global role in renewable energy advocacy.

8.6. Reduction in Greenhouse Gas Emissions- Transitioning to solar energy significantly lowers carbon emissions, contributing to climate change mitigation. It supports India's commitment to the Paris Agreement and Sustainable Development Goals (SDGs).

8.7. Reduced Energy Costs- Large-scale solar deployment can lower energy prices for consumers and reduce subsidies on fossil fuels.

8.8. Energy Independence- Harnessing domestic solar resources reduces reliance on volatile international energy markets.

9. RECOMMENDATIONS

- Policy Simplification: Harmonizing state and central policies to streamline project approvals and incentivize investments.
- Financial Support: Providing low-interest loans, subsidies, and tax benefits for solar energy projects and installations.
- Domestic Manufacturing: Encouraging local production of solar cells, modules, and storage

solutions through programs like “Make in India.”

- Public Awareness: Conducting awareness campaigns to promote rooftop solar and energy efficiency.
- Grid Modernization: Investing in smart grids and storage technologies to manage intermittent solar power supply effectively.

10. CONCLUSION

India's solar energy sector has immense potential to drive economic growth, enhance energy security, and combat climate change. With sustained government support, technological advancements, and global partnerships, solar energy can emerge as a key pillar of India’s energy and economic future. By overcoming existing challenges, India can lead the world in renewable energy adoption and innovation.

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