International Journal of Sustainable Energy Planning and Management Vol. 44 2025 47–58

International Journal of Sustainable Energy Planning and Management

Accelerating Solar Power Generation to Achieve India's Net-Zero Goals: A Factor-Based Study

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ABSTRACT

The commitment of India towards net-zero emissions, as announced at COP26, has led to remarkable transformations in its power sector. Despite being rich in diverse energy resources, India holds substantial potential for solar power generation, which is believed to play a crucial role in its journey toward net-zero emissions. Even though some states of India have achieved great milestones in the solar energy generation, still the progress seems insufficient and there exist regional imbalances. This shortage and imbalance may be attributed to various factors including fiscal, geographical and political elements. From the panel data analysis to identify the most influencing factors of solar power generation across 15 states, the cost of solar modules and the land availability were found to be the major drivers. The practical barriers associated with these factors are highlighted, and relevant potential solutions are proposed. The study insists on promoting rooftop solar as a viable alternative for small-scale initiatives and suggests altering the existing scheme, *Pradhan Mantri Surya Ghar Muft Bijli Yojana,* to ensure real monetary benefits for individuals through rooftop solar systems; progressive subsidy rates; regional subsidy ceilings; and zero-tax for solar PV modules; To facilitate large-scale solar projects, the concept of district-level green land banks has been proposed in the study.

Keywords

Rooftop solar;
Pradhan Mantri Surya Ghar Muft Bijli Yojana;
Income generation;
Progressive subsidy;
Green land bank

http://doi.org/10.54337/ijsepm.9787

1. Introduction

India, one of the largest and fastest-growing economies, is becoming a pioneer in the global renewable energy transition. The reason behind its focus on renewable energy can be highlighted by the fact that its GHG (Greenhouse Gas) emissions have tripled in the last three decades [1]. The commitment of the nation for achieving net-zero emissions by 2070, as announced at COP26 (26th Conference of the Parties), underscores the pivotal role of renewable energy, particularly solar power in transforming its power sector [2]. The unique geographical advantage of receiving around 5,000,000 TWh of solar energy (i.e., approximately 3.5 GWh per capita) annually positions the country as a leader in solar energy potential [3].

However, despite the abundant solar resource, the growth of solar energy generation remains uneven across states due to several fiscal, financial, geographical, and political factors. The solar capacity growth of the country has been significant in recent years, driven by supportive policies and ambitious targets [4]. Certain states, such as Rajasthan and Gujarat, have emerged as solar power leaders due to their favorable geography and policy support, while other states lag behind due to various constraints [5]. These disparities highlight the need for effective policies to expand solar energy generation across India.

As depicted in Figure 1, the power and industrial sectors together contribute a major share toward the Carbon emissions in India [1]. Considering this, recent initiative like the PMSGMBY (*Pradhan Mantri Surya Ghar Muft Bijli Yojana)* to promote rooftop solar systems among households, is a significant move. But the scheme lacks clarity and contains a few shortfalls that could be enhanced

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Received 11.12.2024 | Accepted 09.04.2025 | Published 10.05.2025

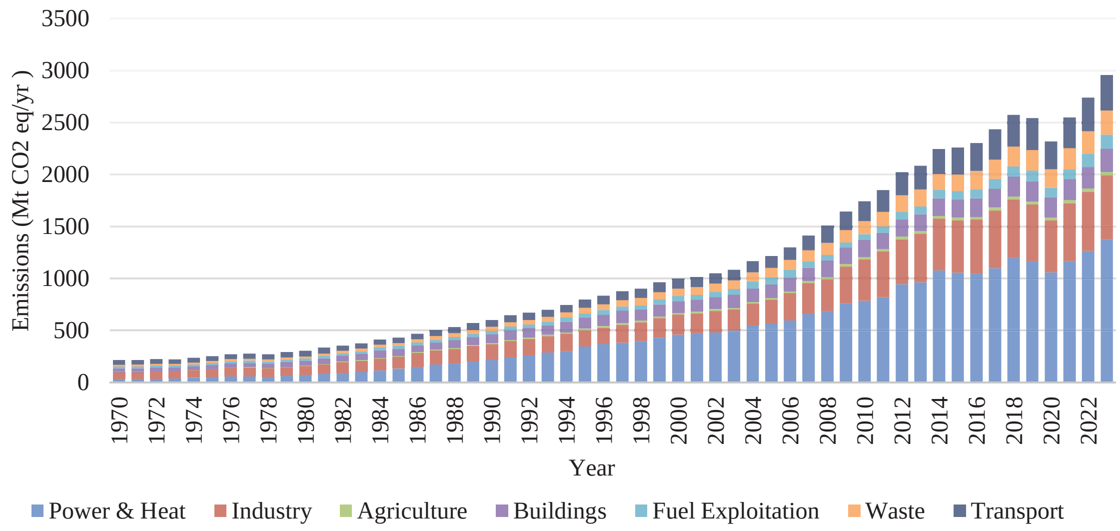


Figure 1: Sector-wise Carbon Emissions in India. Based on data from [1].

through a more tailored approach. Additionally, the stability of the government might be an influencing factor for the complete implementation of such schemes [6].

Studies suggest that the cost of solar technology remains a key barrier to broader adoption across the country [7]. This has made solar investments less attractive in certain regions, particularly where financial incentives are limited [8]. In this regard, India has made import duty exemption for solar modules to bring down the cost of solar panel installations [9]. Moreover, the IREDA (Indian Renewable Energy Development Agency) report has advocated for enhanced financial incentives, including increased subsidies and tax rebates to reduce the burden on consumers and promote solar adoption [3].

While several studies have examined the barriers to solar PV adoption and their contributions to renewable energy targets, research specifically addressing these challenges in the Indian context remains limited [10, 11]. One study has suggested optimal investment strategies, particularly for multi-story buildings, for enhancing residential rooftop solar systems in India, highlighting the need for targeted financial policies to encourage widespread adoption [12]. Given this context, this paper aims to explore the key factors influencing solar power generation across India, focusing on local challenges such as inadequate fiscal policy, financial constraints, land availability, and political stability.

Since the study focuses on rooftop solar systems, the data and the factors for the study have been chosen solely based on the solar PV (Photovoltaic) plants set up across the states. The solar thermal power plants that use reflector technology to capture solar energy are not considered in this study. With analytical evidence, this paper aims to suggest policy changes to address the shortages and imbalances by focusing on rooftop solar systems and large-scale alternatives, thereby accelerating solar capacity growth and contributing to the net-zero emissions goal.

2. Challenges and Opportunities in Solar Energy Adoption

Although India possesses immense potential for harnessing solar energy, it continues to encounter multifaceted barriers that hinder its adoption as a major power source. These challenges can be examined from various perspectives, as outlined in the following subsections.

2.1. Solar Power Generation Disparity

The distribution of solar power generation across Indian states highlights inadequacies and significant regional disparities as represented in Figure 2 [13, 14]. The states with higher generation capacities are depicted in dark circles and the light-coloured circles represent lower capacities. It is often perceived that states with limited fiscal resources are less likely to invest in renewable energy initiatives, impacting overall progress toward national renewable energy targets. Fiscal space, defined as the difference between total revenue receipts and expenditure of a state, determines its capacity to invest in new sustainable initiatives.

This study further explores the impact of fiscal strength of the states on solar energy development in subsequent sections. While fiscal capacity is an important determinant of solar power generation, studies suggest that solar irradiance, though manually uncontrollable, also plays a crucial role in determining solar power output [15]. Solar irradiance, which refers to the quantity of solar energy reaching a given surface area, is a key factor in determining the viability of solar photovoltaic (PV) systems.

Despite the favourable location of the country, receiving about 300 sunny days annually, the intensity and distribution of solar irradiance vary significantly across states, affecting the efficiency and cost-effectiveness of solar power projects [16]. On an average, the solar irradiance levels in India range between 4 to 7 kWh/m²/day [17]. States like Rajasthan, Gujarat, Andhra Pradesh,

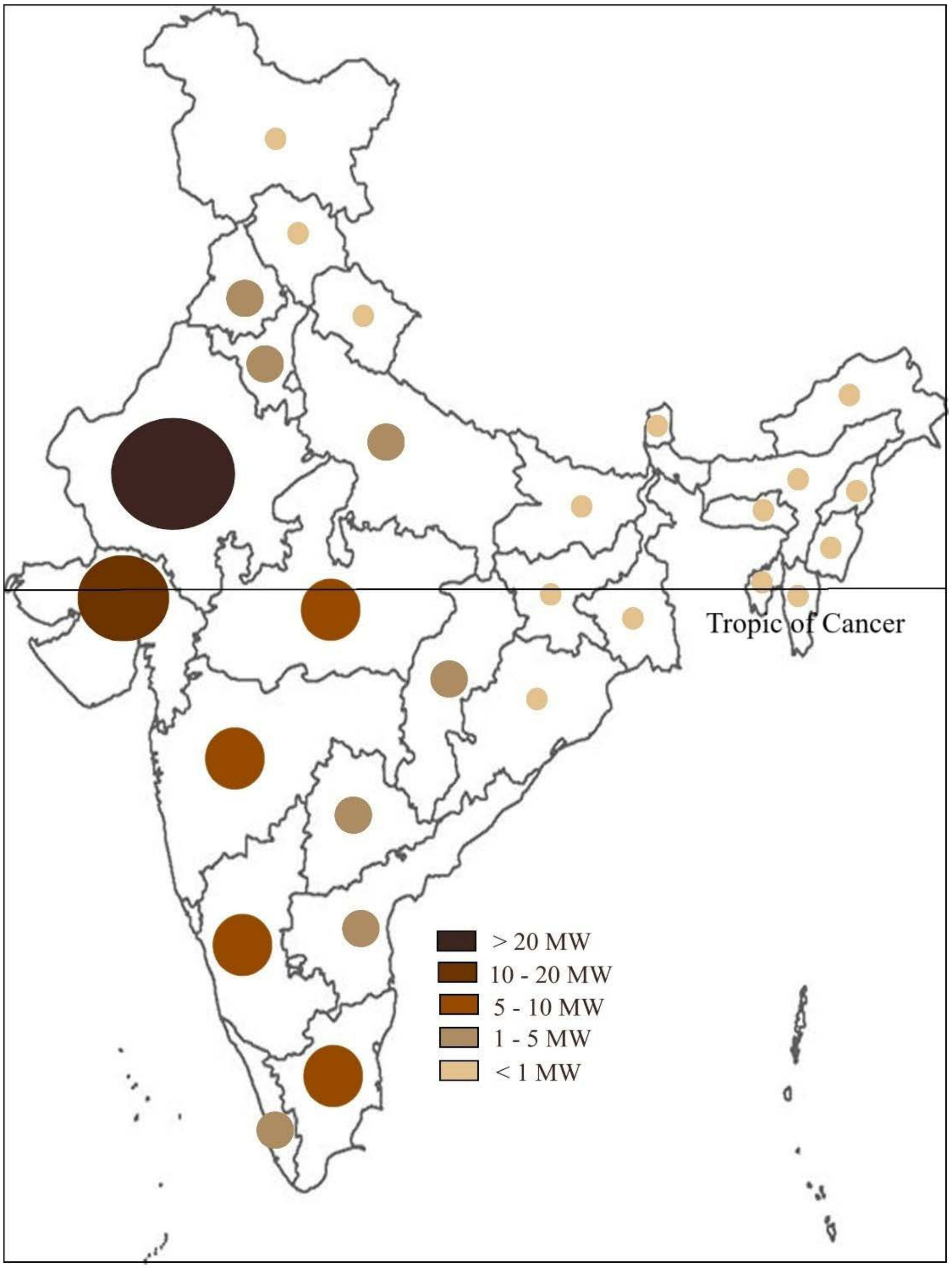


Figure 2: State-wise Regional Disparity in Solar Power Generation Capacity in 2024. Based on data from [14].

and Tamil Nadu experience higher solar irradiance levels (5 to 6 kWh/m²/day), making them ideal for large-scale solar projects [5, 18].

In contrast, states such as Arunachal Pradesh, Himachal Pradesh, and Mizoram receive significantly lower solar irradiance levels (4 to 4.5 kWh/m²/day) [5]. These regions face reduced energy yields due to lower sunlight availability, making large-scale solar projects less economically viable. Regions with higher irradiance are naturally more favourable for efficient energy generation, attracting greater investment. However, the existing subsidy structure in the PMSGMBY appears to be more generalised and misaligned with the actual need. Hence, the subsidy structure of the scheme needs further alterations as discussed in the subsequent sections.

2.2. Barriers to Solar Photovoltaic (PV) Adoption in India

Despite the vast solar potential of the nation, the adoption of Solar Photovoltaic (PV) technology continues to face numerous challenges, including financial constraints, regulatory hurdles, and technological limitations. Despite the falling prices of PV modules in recent years, the high installation costs remain as a significant challenge for the solar power plants [7]. Recent policies aimed at reducing import duties and providing production-linked incentives (PLIs) to boost domestic production of solar panels and equipment are commendable but seem insufficient [19].

The current tax rate of 12% on solar modules significantly contributes to the upfront cost burden for businesses [20]. While indirect benefits, such as accelerated depreciation, offer long-term financial advantages, they do not address the immediate capital constraints faced by Indian firms [21]. The insufficient research and development funding, lack of awareness, limited market network, complex tariffs and inconsistent regulations across states act as major obstacles to solar PV adoption in India [22,23]. Financial constraints, particularly limited access to credit, act as significant barrier to renewable energy adoption [16].

Policies that offer financial schemes and fiscal incentives to small investors can mitigate these challenges and encourage the adoption of latest PV technologies. Delays in the release of subsidies and lack of proper communication about the distribution of subsidies have brought down solar PV adoption, creating uncertainty for potential consumers [24]. Timely disbursement of subsidies and effective communication strategies are essential to develop confidence among solar PV investors, especially among smaller consumers and businesses.

As a move towards enhancing the affordability and accessibility of the solar PV technology among households, the Indian government has introduced the PMSGMBY. The scheme aims to benefit 10 million households with rooftop solar panel subsidies under two criteria: 60% for 1kW-2kW and 40% for 3kW rooftop solar systems [25]. In addition, it has also been proposed that the subscribers of this scheme can generate income by selling the surplus energy produced from their rooftop to the DISCOMs (Distribution Companies) [25].

Here, the major shortfall of the scheme begins with the fact that, the capacity for the rooftop system provided under the scheme will be granted only based on the recorded monthly average consumption of each household [25]. This means that, if a household consumes 200 units on average, it will be granted with a rooftop capacity that is sufficient to cover the equivalent level of consumption. Hence, there are hardly any possibilities for them to generate surplus energy.

Notably, although the electricity market is well regulated by the government, in case households produce excess energy beyond their consumption, the per-unit selling price of this excess energy is fixed much lower than the existing market rate at which the DISCOMs sell their electricity to consumers [26]. As a result of these hurdles, any surplus energy generated through these rooftop systems might be sufficient only to offset their electricity bills, but with an additional monthly payment of a service charge ranging from 5 to 6 USD [27].

Hence, in reality, the scheme could mostly favor only the rich and upper-middle-class sections who pay a monthly lumpsums on electricity bills. In addition, as these rooftop solar systems cease to generate energy during power outages, many will be reluctant to opt for this program, as the scheme fails to cover the rooftop systems with battery backup [27]. Hence, these are the major challenges that need to be addressed to boost the growth of solar PV adoption in India.

2.3. The Role of State Fiscal Policy

The role of fiscal policy has been pivotal in shaping the trajectory of renewable energy development in India. The electricity reform story of the nation has largely revolved around state-level policy measures. Despite central government initiatives, certain states have also followed divergent paths in their clean energy development, regardless of political alignment. For instance, some states like Madhya Pradesh, opted to reject central subsidies in favor of aligning policies with international agencies, while states like Maharashtra were slow to emphasize utility-scale solar energy [28].

This highlights that fostering clean energy in India extends beyond mere central government support; state-level barriers and opportunities must also be considered for long-term renewable energy success. State-level solar policies have been a key factor in the growth of the solar energy sector. For instance, Gujarat witnessed significant solar development after implementing its first state solar policy in 2010, which attracted investors due to low land leasing costs and high solar irradiance [5]. However, after 2014, growth stagnated in states like Gujarat, Rajasthan, and Madhya Pradesh as a result of lack of new initiatives [5].

Meanwhile, states like Tamil Nadu, Andhra Pradesh, and Telangana experienced rapid solar sector growth due to more favorable state policies [5]. This highlights the role of states in providing subsidies and tax exemptions to boost renewable energy adoption. Apart from mere provision of subsidies, there are many other factors that determines the actual development. The willingness of financiers to invest in renewable energy projects depends on the perceived risk in the sector. Durable and attractive fiscal policies are essential to mitigate these risks and consistent development.

Lack of policy clarity and transparency can severely hinder long-term planning and growth in renewable energy development [29]. However, inconsistent regulatory frameworks across states, such as differing renewable purchase obligations (RPOs), pose risks for investment in the sector [30]. This stresses the need for national-level fiscal incentives and a unified regulatory structure to encourage private and foreign investments in renewable sector.

For instance, mature government measures, such as auction policies have played a crucial role in attracting local and foreign investors to the renewable energy sector [8]. However, the sector has faced institutional challenges, such as poor inter-departmental collaboration and improper communication [31]. Studies have suggested that national-level renewable purchase obligations (RPOs) need to be enforced more rigorously to drive demand for solar energy [32].

2.4. The Role of Political Stability

In general, political stability plays a crucial role in determining the ability to achieve long-term goals of a nation. In the Political Stability Index, which ranges from -2.5 to 2.5, India has scored -0.64, indicating that the country faces moderate challenges to its political stability [33]. In India, government involvement in national trade, along with ministerial transitions, has been a significant barrier to the acquisition of renewable energy technologies [16]. The lack of consistent policy frameworks further worsens this challenge.

While policies have been developed as needed to address specific technological advancements such as solar PV, a cohesive long-term strategy remains absent [16]. For instance, the Energy Conservation Act initiated the Bureau of Energy Efficiency (BEE) to promote energy conservation and efficiency across the economy. However, despite its mandate to enforce energy efficiency standards, the BEE has yet to fully exercise this authority, revealing gaps in governance and regulatory enforcement [16].

Similarly, the development of offshore wind energy faces significant delays due to the absence of dedicated policies, emphasizing the need for greater political commitment [16]. Hence, political alignment with the central government also plays a role; states aligned with the center often have larger advantage, enabling them to secure more resources for development, including renewable energy projects. Political stability of any government is essential for maintaining consistent revenue flows and discretionary spending, which can be effectively channeled into infrastructure and renewable energy projects.

For instance, the complete implementation of PMSGMBY has been proposed over a three-year period, ending in 2027 [25]. In such cases, the long-term stability of the government might be a deciding factor for successful implementation of such schemes. In democratic systems, like India, governments must continually generate sufficient revenue to fund initiatives that support their electoral prospects. While renewable energy accounted for 38% of the total installed energy capacity in 2020, making India the third-largest renewable energy producer globally, issues related to infrastructure and political inconsistencies continue to pose challenges [6].

Political instability can aggravate these challenges by promoting short-term, opportunistic policies, such as expanding power subsidies to gain electoral support from farmers, which hinders long-term infrastructure development and sustainable growth. Overall, stable governance not only ensures the formulation of consistent policies but also facilitates the effective allocation of fiscal resources, which are vital for achieving the ambitious renewable energy targets.

This paper provides a comprehensive analysis of the practical challenges faced by solar power plants in India. Unlike previous studies that primarily focus on numerical data, this study stands out by offering practical solutions to promote balanced solar power acceleration across the country. A factor-based analysis is conducted in the subsequent sections to identify the most influential factors affecting solar power generation. Based on the findings, the study emphasizes rooftop solar systems as an effective solution to power India. Furthermore, the practicality of existing solar scheme, the fiscal status of government and other related barriers are thoroughly discussed.

3. Analytical Evidence for the Major Factors

The study examines the key determinants influencing renewable energy generation, with a particular focus on solar energy production in India. The primary factors analyzed include the Price Index, Net State Domestic Product (NSDP), barren land availability, and political stability.

- Price Index: The price index of solar modules is directly linked to installation costs. As a general economic principle, higher costs typically reduce demand, making the price index a crucial factor in determining solar adoption.
- NSDP: The NSDP reflects economic capacity of a state to support large-scale projects, including prioritizing renewable energy initiatives over other welfare schemes.
- Barren Land Availability: The availability of barren land plays a significant role in the feasibility and scalability of solar projects. States with abundant barren land, such as Gujarat and Rajasthan, are better positioned for large-scale solar farms [34].
- Political Stability: Political stability is another critical factor, as consistent long-term policies and strong investor confidence are essential for attracting investments in solar energy projects.

These four factors were selected based on their relevance to solar energy generation. Data for these variables were collected from Indiastat and the World Bank, covering a nine-year period from 2013 to 2021 [33,34-37]. The price index data represents the wholesale price index of solar PV modules in India, using 2011-12 as the base year. For the analysis, the price index, NSDP, and political stability data are expressed as percentage values, while the data for solar power generation and barren land availability are transformed into logarithmic values.

The analysis includes a panel dataset representing 15 Indian states, selected based on the criterion of achieving a minimum solar energy production of 100 MWh per year during the specified timeframe. The states considered in this study include, Andhra Pradesh, Chhattisgarh, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamil Nadu, Telangana, Uttar Pradesh, Uttarakhand. The values of solar power generation of these states have been taken as the dependent variable and the exogeneous variables include Price index, Net State Domestic Product, Barren land and Political stability index.

The regression equation model for the study is shown below in Eq. (1):

$$Y_{it} = \alpha + \beta X_{it} + u_i + \varepsilon_{it} \qquad - (1)$$

where:

- Y_{it}: Dependent variable
- X_{it}: Exogeneous variables
- α: Individual effect
- β: Unknown parameter
- u_i: Individual residual (random unit observation)
- ε_{it}: Collective residual (combination of both time series as well as cross section)

The metrics of the descriptive statistics for these variables were examined, revealing minimal deviations, making it appropriate for the analysis. Also, from the correlation analysis results shown in Table 1, there are no significant traces of multicollinearity. Im-pesaran-shin unit-root test was used to check the stationarity of the variables. Once the variables were found appropriate for the analysis, the panel regression model was proceeded to study the influence. To choose the suitable model between fixed-effect and random-effect models, the Hausman test was used. The null hypothesis of the Hausman test states that the difference in coefficients between two models is not systematic. In that case, since the p-value is 0.571 (see Table 2), the null hypothesis fails to be rejected. Hence, the random effect model was chosen for the study and the regression analysis was carried out.

4. Results and Discussion

As discussed earlier, the exogeneous variables include, price index, NSDP, barren land availability and political stability index. The regression output of the random

Table 1: Correlation Analysis of the Factors influencing Solar Energy Generation.

	Price Index	NSDP	Barren Land	Political Stability
Price Index	1	0.3969	0.0068	-0.0206
NSDP	0.3969	1	0.1050	-0.1391
Barren Land	0.0068	0.1050	1	0.0069
Political Stability	-0.0206	-0.1391	0.0069	1

effect model is shown in Table 3. The value of R-squared (within) - 0.8003, indicates that the model explains 80% of the variation in solar energy generation within states. Similarly, the R-squared (between) - 0.6171, explains 61.7% of the variation between states. And the overall fit is shown through the R-squared (Overall) - 0.7103, explaining 71% of the total variation in solar energy generation among the states. The Wald chi-squared test value of 482.28, with a p-value of 0.0000, indicates that the model is statistically significant. Overall, the model fits the data well, and the Wald test confirms its significance. Hence, the further inferences are made in the subsequent sections.

4.1. Price Index

The coefficient of price index is negative and significant at the 1% level (p-value: 0.000). This imply that there exists an inverse relationship between the price of solar modules and solar power generation. Hence, per-unit increase in the price index limits the solar energy generation by about 0.155 MWh, holding other factors constant. Therefore, the cost of solar modules, reflected in the price index, plays a crucial role in influencing solar energy generation across Indian states. Considering such a relation between the two, the recent hike in the tax rate on solar modules from 5% to 12% significantly increases the upfront cost of solar plants [38].

Although this tax generates approximately 449 million USD in revenue, it constitutes only 0.07% of the total government revenue [39]. While this revenue has minimal impact on the overall finances of the government, the increased tax represents a significant financial burden for individuals and businesses. Consequently, placing solar modules under a tax-exempt category could possibly enhance the affordability and attractiveness of solar plant projects.

Policies that promote favorable power purchase agreements (PPAs) and simplify tariff structures could incentivize both entrepreneurs and households to contribute to rooftop solar power generation for commercial purposes by collaborating with firms [40]. Provided the fact that the cost of solar modules is a significant factor, initial cost of setting up huge solar plants could be a major reason for its unbalanced distribution across the states. Hence, encouraging subsidized rooftop solar systems could accelerate solar adoption across residential as well as commercial entities in a more uniformed manner.

Table 2: Hausman Test to choose between Fixed Effect Model and Random Effect Model.

	Coef.
Chi-square test value	2.922
P-value	.571

Table 3: Panel Regression Output of the Factors Influencing the Solar Energy Generation.

Solar_energy_ generated	Coef.	S.E	t-value	p-value	[95% Conf	Interval]
price_index	-.155	.008	-20.18	0	-.17	-.14
nsdp	.014	.016	0.88	.381	-.018	.046
barren_land	.711	.19	3.75	0	.339	1.083
political_stability	-.005	.004	-1.40	.163	-.012	.002
constant	4.906	2.51	1.95	.051	-.014	9.826

Overall r-squared	0.710	Number of observations	133
Chi-square	482.279	Prob > chi^2	0.000
R-squared within	0.800	R-squared between	0.617

4.1.1 Rooftop Solar Systems: A Practical Approach

For a balanced growth of solar power generation across the nation, having rooftop solar system in every household is an effective solution. Again, the financial burden involved in implementing such rooftop solar schemes is a notable factor. As highlighted in Figure 3, a significant portion of energy subsidies is allocated to the transmission and distribution sector, i.e., DISCOMs [39]. A significant portion of these subsidies is allocated to providing low-cost electricity to households and free electricity for irrigation purposes [39]. However, such subsidies are often misused by large farmers and wealthier sections of society.

This considerable expenditure on electricity subsidies could be better utilized by redirecting it to support economically disadvantaged and middle-class households through programs like the PMSGMBY and PMKUSUM (*Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan Yojana)*.

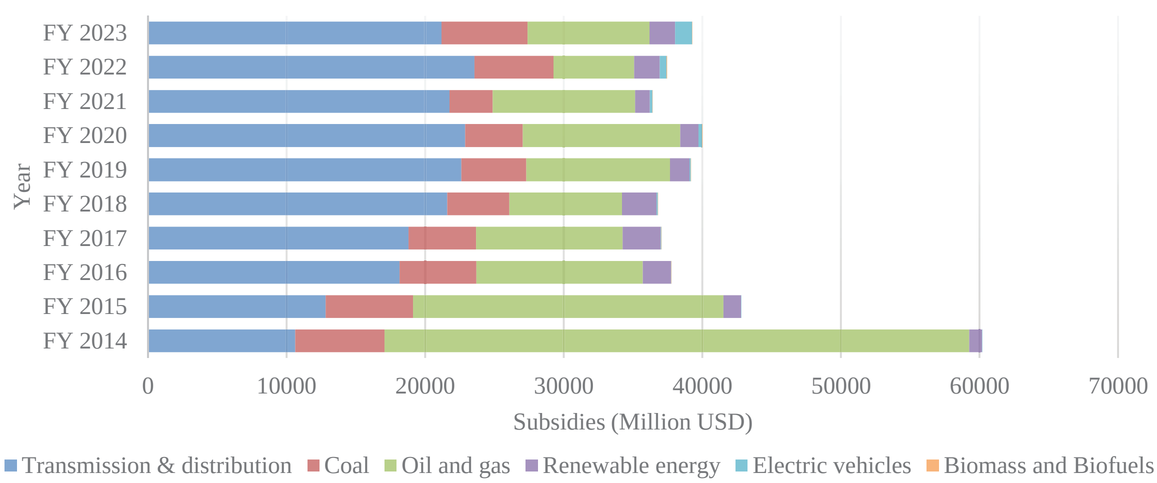
Unlike conventional electricity subsidies, which are short-sighted and offer only temporary relief without encouraging investments, subsidies directed toward rooftop solar schemes contribute to the nation's gross fixed capital formation. These investments strengthen solar infrastructure and provide long-term benefits. While it may not be feasible to eliminate existing conventional subsidies immediately, the government should gradually realign its financial priorities by effectively channeling these subsidies toward more sustainable initiatives in the coming years.

The PMSGMBY, aimed at promoting rooftop solar adoption among the public, is a powerful scheme with immense potential for the near future. The scheme is projected to add approximately 30 GW to the solar energy capacity of the nation, thereby reducing carbon emissions by 720 Mt over the lifespan of these solar panels [25]. Given that India has an estimated total of 300 million households, the nation has the potential to add close to 900 GW to its renewable energy capacity, potentially reducing emissions by 21.6 Gt over the lifespan of these panels [41].

Moreover, it is estimated that the scheme could save the government up to 8.5 billion USD annually by reducing the electricity subsidies currently borne by the government [25]. Although the PMSGMBY offers numerous benefits, it also faces several practical challenges, as discussed in section 2.2. Firstly, the recent increase in tax rates from 5% to 12%, along with periodic service charges, poses significant barriers for the general public [38]. The scheme was initially intended to generate income for households through net metering, but the actual features of the scheme are contradicting with this goal [25].

To improve the efficiency of the PMSGMBY, removing the current 3 kW cap on rooftop solar capacities could substantially increase the energy generation potential for each household. Additionally, purchasing surplus energy generated by household rooftop systems at market-equivalent rates, rather than the low rates currently

Figure 3: Sector-wise Energy Subsidy by the Government of India. Based on data from [39].



offered, could provide a stronger incentive for adoption among economically disadvantaged sections. This change would create genuine income-generating opportunities for common people, as well as stimulate significant employment in rooftop solar installations, ultimately boosting their economic standards.

Additionally, the implementation of progressive subsidies, where subsidy rates increase as income levels decrease, would promote equitable development and prevent the government from allocating excessive subsidies to wealthier groups. This approach would allow the government to more efficiently allocate funds to support the economically weaker sections. To encourage broader adoption of rooftop solar systems, the scheme should be marketed not just as a social initiative but as an income-generating opportunity. Slogans like “Earn with Solar” could effectively highlight the financial benefits of the program, attracting wider participation.

With these proposed improvements, rooftop solar systems could not only empower individual households but also have the potential to power large commercial entities, provided that appropriate power purchase agreements (PPAs) are designed to benefit the public.

4.2. Net State Domestic Product (NSDP)

The coefficient of NSDP is positive, but statistically insignificant (p-value: 0.381). This indicates that the variations in NSDP among the states do not significantly influence solar energy generation in the model. NSDP, that is, the economic performance of states does not have a notable impact on their solar power generation. This finding suggests that the financial strength of a state is not inherently linked to its solar power generation potential. Consequently, solar energy projects should not be restricted to economically advanced states. Underdeveloped states can also be prioritized for innovative solar initiatives, provided they have suitable land resources and adequate policy support.

Considering the unequal development of solar power generation capacities, as depicted in Figure 2, the introduction of region-specific subsidy ceilings is essential to achieve uniform capacity across states. As previously discussed, solar irradiance significantly impacts solar power potential across the nation. States with lower solar irradiance levels require higher subsidy ceilings compared to those with better irradiance. Given the diverse geographical features of the nation, granting state governments the autonomy to modify central schemes according to regional needs could enhance the efficiency of these initiatives.

Introducing region-specific subsidy ceilings under the PMSGMBY could help reduce the existing regional disparities in solar generation capacities. This approach would enable northern and northeastern states to contribute more substantially to national solar power generation, as their current share remains disproportionately low [14]. Therefore, targeted interventions in these regions, including central government-supported projects, can significantly enhance their solar energy contributions while fostering equitable development across states.

While state-level measures significantly influence the success of renewable initiatives, a consistent central government fiscal policy and regulatory framework, as discussed in section 2.3, are equally important in boosting investor confidence, mitigating financial constraints, and ensuring sustained growth in the renewable energy sector.

4.3. Barren Land Availability

The coefficient of barren land is positive and significant at the 1% level (p-value: 0.000). A one-unit increase in the barren land availability leads to an increase of about 0.71 MWh in solar energy production. The results directly depict that, an increase in the availability of barren land gives more space for the installation of solar panels, and hence, acting as a crucial factor for solar power projects. States with more barren or unused land seem to generate more solar energy. Therefore, states with abundant barren land, like Gujarat and Rajasthan, should focus on utility-scale solar farms, while densely populated states, with limited land availability should prioritize rooftop solar and small-scale solar initiatives.

The PMSGMBY serves as a viable solution to tackle the lack of sufficient barren land availability. But again, the usage of rooftop solar as an alternative is limited to small scale solar projects due to its technical inefficiencies. For large scale solar farms, the government should incentivize states to identify and facilitate the allocation of non-agricultural barren land to entrepreneurs. Framing policies to streamline the land acquisition process for renewable energy projects can help the states act efficiently and increase their solar capacity. Also, the concept of “Green land banks” can be introduced to aggregate and utilize the unused barren land, facilitating solar power firms to easily access them for large-scale projects.

4.3.1 Green Land Banks: For Large Scale Generation

The concept of green land banks (GLB) offers a viable solution to utilize barren lands scattered across rural and urban India, that are unsuitable for agriculture or residential purposes. Currently, the lack of data about availability of such lands and unclear ownership records hinder their utilization for projects like solar plants [42]. The green land banks can serve as a bridge to address the gap by maintaining a centralized digital database of underutilized lands from each district across the country. This system allows individuals to register their properties for sale, enabling government and private entities to utilize these records for acquiring land to establish solar power plants nationwide.

Not only does this initiative facilitate the efficient allocation of land for solar energy projects, but it also provides immediate financial assistance to poor and middle-class individuals, particularly those owning barren land. To ensure fairness, the green land banks will determine land prices, guaranteeing that landowners receive the market value for their properties. Consequently, it promotes inclusive growth and decentralized solar energy development. In this way, these green land banks differentiate themselves from the existing model of land banks which primarily focus upon real estate and infrastructure.

4.4. Political Stability

The coefficient of political stability is negative and statistically insignificant (p-value: 0.163). Though the political stability does not have a significant impact on solar energy generation, uncertainties in the state politics could be a barrier over time. Consistent long-term policies across different political regimes and a good political environment are essential to achieve the renewable energy targets [43]. Governments should aim for bipartisan support of solar policies to ensure that investments in solar energy are not disrupted by political changes. Encouraging transparent regulatory frameworks and providing confidence to investors in terms of subsidies and tariffs can help offset any political risk and attract more private investments in solar energy.

5. Conclusion

This study examines the critical factors influencing solar power generation across Indian states, revealing key insights into the challenges hindering solar energy development. The findings highlight that the cost of solar modules and the availability of barren land are major drivers of solar energy generation. To address these two barriers involved in solar power projects, the study puts forward the existing rooftop solar initiative as the viable solution, as it can combinedly solve the issue of huge upfront costs and lack of barren land availability.

Though the rooftop solar scheme like PMSGMBY is already implemented in a wide range, the scheme needs further improvements as suggested in the study. Strategic interventions by altering the scheme in such a way to provide real monetary benefits for households; placing solar PV modules in tax-exempt category; implementing progressive subsidy rates and state-wise regional subsidy ceilings; can significantly accelerate uniform solar power adoption across India.

Additionally, it is suggested that the government can avoid providing one-time benefits like conventional electricity subsidies through DISCOMs, and instead, should allocate funds wisely to contribute to gross fixed capital formation, yielding long-term benefits. Furthermore, in a nation like India, where securing a basic livelihood remains a challenge for many, expecting widespread participation in emission reduction efforts without prior integration of equitable policy incentives may appear impractical. Therefore, this research advocates for policies that reframe rooftop solar initiatives as income-generating opportunities for individuals rather than purely social contributions.

As discussed earlier, the potential of these rooftop solar systems is limited to power only small-scale initiatives. Therefore, the study establishes the concept of district-level "Green Land Bank" that could facilitate the process of identifying unused barren land across the regions and saves time and effort involved. These green land banks enable landowners, particularly those who are financially struggling and in need of funds, to generate immediate income by selling their unused barren land for solar energy projects, thereby fostering inclusive growth and widespread public engagement.

By positioning solar energy as a viable source of income, these initiatives can encourage stronger public participation and reduce financial hesitations. Additionally, while economic indicators like NSDP and political stability exhibit limited influence, consistent and transparent policies along with state-specific measures are vital for building investor confidence and ensuring continuous progress. By effectively utilizing fiscal policy and implementing the above recommended measures, India can achieve balanced solar power development, aligning its renewable energy goals with the broader ambition of net-zero emissions.

To achieve uniform development and sustainable growth of solar energy across India, a blend of robust central government regulatory frameworks and flexible state government autonomy is required. Overall, the study provides actionable guidance for policymakers to overcome existing challenges in solar power adoption and harness the full potential of solar energy across the nation.

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