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Nanotechnology for Rural Solar Solutions: Understanding Social Readiness and Technical Viability

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Abstract
This theoretical review looks at the link between the technical feasibility and social acceptance of solar nanomaterials for photovoltaic use in rural India. It relies solely on existing literature without conducting surveys or fieldwork. Recent developments in nanomaterials like graphene, carbon nanotubes (CNTs), metal oxides (like TiO_2), and quantum dots (QDs) show efficiency improvements of up to 44% due to better light absorption, charge transfer, and thermal management. This makes them suitable for off-grid energy solutions in rural areas. However, there are still challenges such as scalability, stability, and high production costs. Social acceptance depends on views about economic benefits, reliability, and trust in service providers. Barriers like rural-urban inequality, distrust of the private sector, and gaps in awareness decrease support. This paper suggests a new Socio-Technical Acceptance Framework (STAF) that combines technical metrics with social factors to provide a new perspective for policy-making aimed at improving equitable adoption. The conclusions highlight the importance of awareness-driven programs and subsidies to connect technical feasibility with social acceptance. This approach can help advance sustainable energy transitions in under-resourced rural areas.

Keywords
Solar nanomaterials; Renewable energy; Rural India; Social acceptance; Sustainable growth

1 Introduction

Energy remains one of the most essential foundations for both human progress and economic prosperity. The relationship between a nation's development and its energy use is inherently reciprocal: economic growth drives higher energy demand, while stable access to energy resources sustains that very growth. In India, this link is especially visible through a stark contrast between its urban and rural regions. Cities benefit from better infrastructure and access to power, whereas a large part of rural India still struggles with energy scarcity, even after more than seventy years of independence.

National programs such as the Jawaharlal Nehru National Solar Mission (2010), which aimed to achieve 100 GW of solar capacity by 2022, have made progress but not yet bridged the rural–urban divide. Like many economic challenges, this persistent energy gap invites technological interventions. Recent advances in solar nanomaterials, combined with effective public engagement and trust-oriented policies, could offer a sustainable route to narrowing this divide and promoting inclusive growth.

Traditional silicon-based photovoltaic (PV) systems, though widely deployed, have limitations—particularly concerning efficiency, cost, and environmental adaptability in decentralized rural contexts. In response, researchers have increasingly turned to nanomaterials, engineered at the 1–100 nm scale, which show improved optical absorption, charge transport, and heat management capabilities, thereby enhancing overall solar cell performance.

However, no technological breakthrough can succeed without social acceptance. For innovations such as solar nanomaterials to be impactful, they must resonate with the social realities and perceptions of rural communities. While urban households often experience solar energy through indirect environmental gains or slightly reduced electricity bills, rural India stands to experience much deeper transformation—reliable lighting, extended work hours, and better livelihood opportunities. Yet, successful integration depends not only on technology but also on the economic, cultural, and institutional systems that influence local decision-making.

This paper reviews existing literature on the technical feasibility and societal acceptance of solar nanomaterials in rural India. It relies entirely on secondary data drawn from peer-reviewed journals, official reports, and credible databases. The study's distinct contribution lies in proposing a Socio-Technical Acceptance Framework (STAF) that links performance metrics from material science with insights from social theory. By connecting these perspectives, the framework identifies practical relationships and policy pathways often overlooked in earlier studies that treated social and technical aspects separately. Ultimately, this integrated approach seeks to guide strategies that mitigate energy disparities and align with the broader goals of India's Vision 2047—a roadmap toward sustainable and inclusive national development.

2 Literature Review

This section synthesizes recent literature on two interrelated themes: the technological viability of solar nanomaterials and the societal acceptance of solar technologies in rural India. It reviews key findings, methodologies, and implications drawn from peer-reviewed studies published between 2018 and 2025.

1. Technological Viability of Solar Nanomaterials

Recent scholarship highlights how nanomaterials are reshaping photovoltaic (PV) technologies, especially in environments where resources and infrastructure are limited. These materials are increasingly viewed as catalysts for improving both the efficiency and adaptability of solar systems.

1.1 In their 2025 review, Kumar et al. examine functional nanomaterials used in renewable energy technologies and demonstrate how compounds like graphene, carbon nanotubes (CNTs), metal nanoparticles, and metal oxides like *titanium dioxide* (TiO_2) and *cerium dioxide* (CeO_2) enhance solar-cell performance. These materials increase electrical conductivity**,** surface area**,** and optical absorption, all of which directly influence photovoltaic output.

Nanoparticle coatings, for instance, are shown to improve light trapping and provide anti-reflective properties, while graphene and CNTs contribute to lighter and more conductive devices. The review reports measurable efficiency gains arising from better charge transfer in both solar and hydrogen fuel systems. Yet, it also draws attention to persistent challenges—particularly the difficulties of large-scale synthesis and commercialization. The authors emphasize the need for more applied research that can bridge the gap between laboratory progress and field-ready technologies for developing regions.

1.2 Adding to this body of work, Sharma et al. (2024) review how nanomaterials improve the efficiency and affordability of solar collectors and fuel cells, particularly in emerging economies. Their findings reaffirm that metal oxides and nanoparticles can substantially enhance operational performance. However, they also caution against drawbacks such as particle clustering**,** increased viscosity of nanofluids**,** and environmental risks that may arise during disposal or large-scale deployment.

1.3 Complementary insights appear in a 2023 article in Wiley Energy Reports, which discusses the role of nanomaterials in energy storage and thermal management. It highlights how CNT–H_2O nanofluids improve light-to-heat conversion, indirectly enhancing the performance of batteries and super capacitors —systems crucial for supporting solar-based energy integration. Together, these studies underscore the multifaceted value of nanomaterials across solar generation, storage, and thermal applications, even as practical implementation challenges persist.

Collectively, these studies underscore the promise of nanomaterials in advancing third-generation photovoltaic systems that surpass traditional efficiency limits. Yet, scalability, long-term stability, and cost remain critical obstacles to widespread deployment in rural contexts.

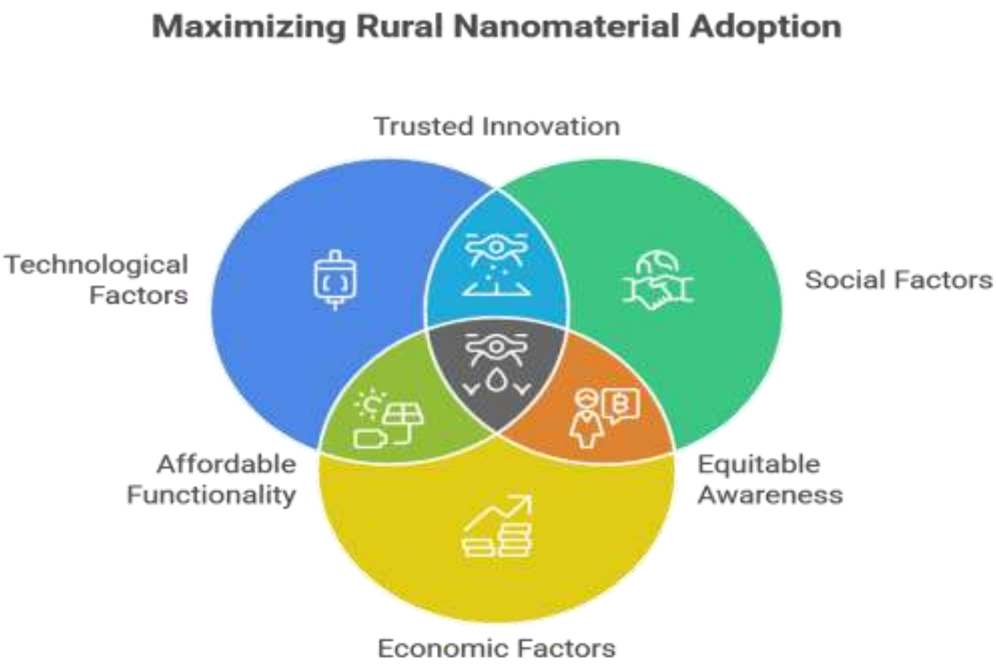


Figure 1 Key factors influencing rural adoption of nanomaterials: balancing technology, economy, and society

2. Government Policies, NITI AYOG and India Vision 2047

2.1 As of July 2023, the total Renewable Energy installed capacity in the country stand at177.74 GW, as the statistics by a Policy Paper on the official site by NITI Aayog published in 2024. According to the findings of the study, an additional 269.79 GW of capacity can be generated within the state's existing potential, while approximately 69.81 GW would need to be sourced from other states. To achieve the Renewable Purchase Obligation (RPO) target by 2029–30, the total required installed capacity stands at 517.34 GW, out of which 177.74 GW has already been established, leaving a remaining 339.6 GW yet to be developed.

2.2 PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) Scheme targets to ensure energy security Indian farmers. As part of Intended Nationally Determined Contributions (INDCs), India commits to increase the share of installed capacity of electric power from non-fossil-fuel sources to 40% by 2030.

2.3 Prabhakar Yadav et al. in his paper highlight the prospects of decentralized solar energy. It underscores that India has had a long history of off-grid solar application, stemming from the oil crisis in the 1970s. India has been using various mechanisms over the past four decades. Ranging from early demonstration projects, philanthropic initiatives, subsidy and public grants-based programs, and market-based mechanisms, including retail and Pay-As-You-Go (PAYG) -based installations to disseminate solar PV products, such mechanisms have pivoted the way to solar revolution.

This sector saw systematic and significant development with the announcement of the national solar program in 2010, followed by increasing private sector investment and innovations. Key programmes supporting off-grid solar, summarized in figure - 2, represent major initiatives of the national government that are implemented through national or state nodal agencies, commercial banks, and private suppliers.

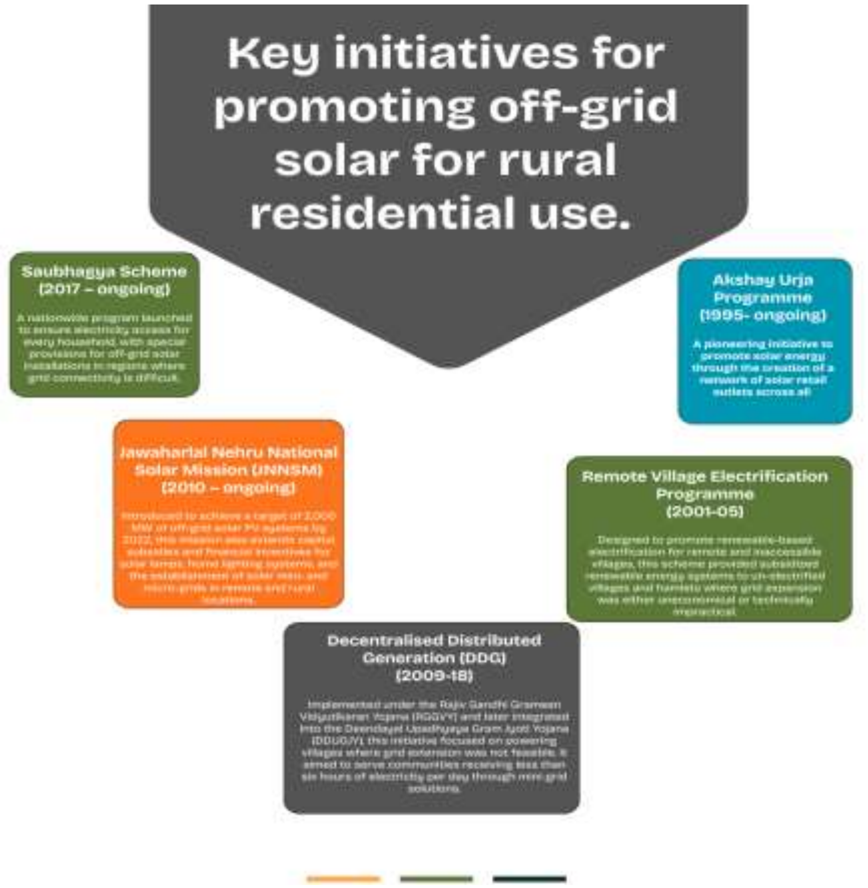


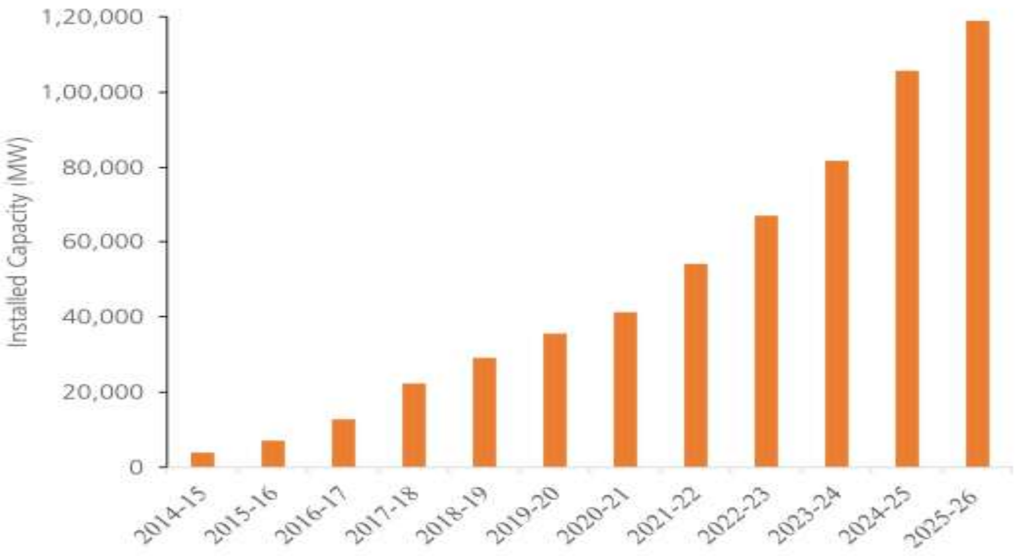
Figure 2 Government programs supporting rural off-grid solar deployment across India.

However, many a multifaceted challenge is yet to be addressed fully. Distribution and procedural energy justice issues are there, they may range from how to successfully negotiate and deliver partnerships between public and private actors, how to provide the required capital, operational efficiencies, and new business practices to how to drive solar PV-based energy transition well.

As per the chart officially available on the website of the Ministry of New and Renewable Energy, we can see a rise in the renewable solar energy production.

3. Societal Acceptance of Solar Technologies in Rural India

Figure 3 Year-wise installed Solar PV potential (till July 2025) capacity in India.



Reviewing these papers display the acceptance of technological innovations in rural India with respect to perceptions, various economic factors, trust in private and government stakeholders, recent experiences of end users and the role of other institutions.

3.1 Aklin et al. (2018) conducted a large-scale framing experiment involving 3,208 villagers across six northern Indian states to assess attitudes toward off-grid solar adoption. Frames emphasizing private-sector involvement reduced support by 0.07 standard deviations due to perceived risks of exploitation, while messages focusing on rural–urban inequality decreased support by 0.081. In contrast, government- and price-related frames had milder effects. The study highlights pervasive distrust toward both private and public actors, coupled with higher solar costs relative to subsidized grid electricity. These findings underscore the importance of addressing inequality and rebuilding institutional trust to foster broader adoption.

3.2 Sharma (2020) analyzed a solar microgrid project in Dharnai, Bihar, using frameworks such as the Social Construction of Technology (SCOT) and Public Understanding of Science (PUS). Although promoters framed the initiative as a model of sustainable innovation, villagers labelled it “fake energy” because of unreliable service and high costs (₹9/kWh compared to ₹3/kWh for grid electricity). As a result, connections fell from 255 to 120 households, influenced by caste disparities, economic constraints, and expectations of government support. The study illustrates how socio-political and functional factors can outweigh environmental benefits in shaping public acceptance.

3.3 In a survey of 516 rural households in Prayagraj, Kumar and Kaushal (2022) applied the Unified Theory of Acceptance and Use of Technology (UTAUT2). Government policy support and facilitating conditions emerged as the strongest predictors of behavioral intention to adopt solar systems. Although awareness (70.35%) and performance expectancy positively influenced adoption, limited economic capacity constrained actual implementation. The authors recommend targeted subsidies and demonstration programs to enhance acceptance.

3.4 Yadav et al. (2025) investigated perceptions of solar lighting systems among 153 marginalized households in West Bengal. Using principal component analysis, they found that awareness, ease of use, performance, and perceived economic benefit explained 70.68% of the variance in adoption behavior. Low education levels and affordability barriers persisted, but awareness campaigns and training interventions were identified as effective mediators, consistent with the Technology Acceptance Model (TAM).

Collectively, these studies reveal that social acceptance of solar technologies in rural India depends not only on technical performance but also on framing, awareness, affordability, and equity. Addressing these dimensions is essential for bridging the gap between technological innovation and community-level adoption.

Nanomaterial	**Efficiency Gain**	**Application**	**Challenges**
Graphene/CNTs	Up to 10% conductivity improvement	Electrodes, batteries	Scale-up expense
TiO_2/Metal Oxides	9.3-10.2% in DSSCs	Charge transfer	Moisture instability
QDs (PbSe)	>100% quantum efficiency	Multi-exciton generation	Toxicity, recycling
Nanofluids (Al_2O_3)	5-28.3% thermal	PV/T cooling	Viscosity, clustering

Table – 1 Comparative Efficiency of several Nanomaterials.

Evidence from reviews indicates rural off-grid potential, but Indian viability hinges on cost minimization (e.g., thin-film technologies) and handling environmental concerns. Gaps: Few India-specific trials; scalability is theoretical.

3 Societal Analysis

Understanding factors are awareness (70.68% variance) and policies (β=0.207), but negative framing decreases support by 0.07-0.081 SD. Barriers figure:

Figure 4 Major barriers influencing rural technology adoption and their corresponding impacts.

Qualitative findings reveal rejection because of "fake energy" feelings and caste dynamics. Interrelations: Economic obstacles magnify social resistance.

Novel Synthesis: Socio-Technical Acceptance Framework (STAF)

The transition toward renewable energy in developing nations like India demands not only technological advancement but also societal acceptance. To address this dual requirement, the Socio-Technical Acceptance Framework (STAF) is proposed as a novel approach that merges technical performance indicators with social and behavioral insights. The essence of STAF lies in understanding that innovation alone cannot ensure progress unless it aligns with community needs, perceptions, and participation.

Unlike earlier frameworks such as UTAUT2 (Unified Theory of Acceptance and Use of Technology), which primarily examine user behavior and intention in technology adoption, or SCOT (Social Construction of Technology), which focuses on how social contexts shape technological meaning, the STAF model emphasizes the *co-evolution* of both domains. It bridges the gap between lab-scale technological promise and on-ground social realities. This integration is especially relevant for solar nanomaterial applications in rural India, where the success of innovation depends equally on efficiency and equity.

The following figure.04 describes the key areas where focus is needed.

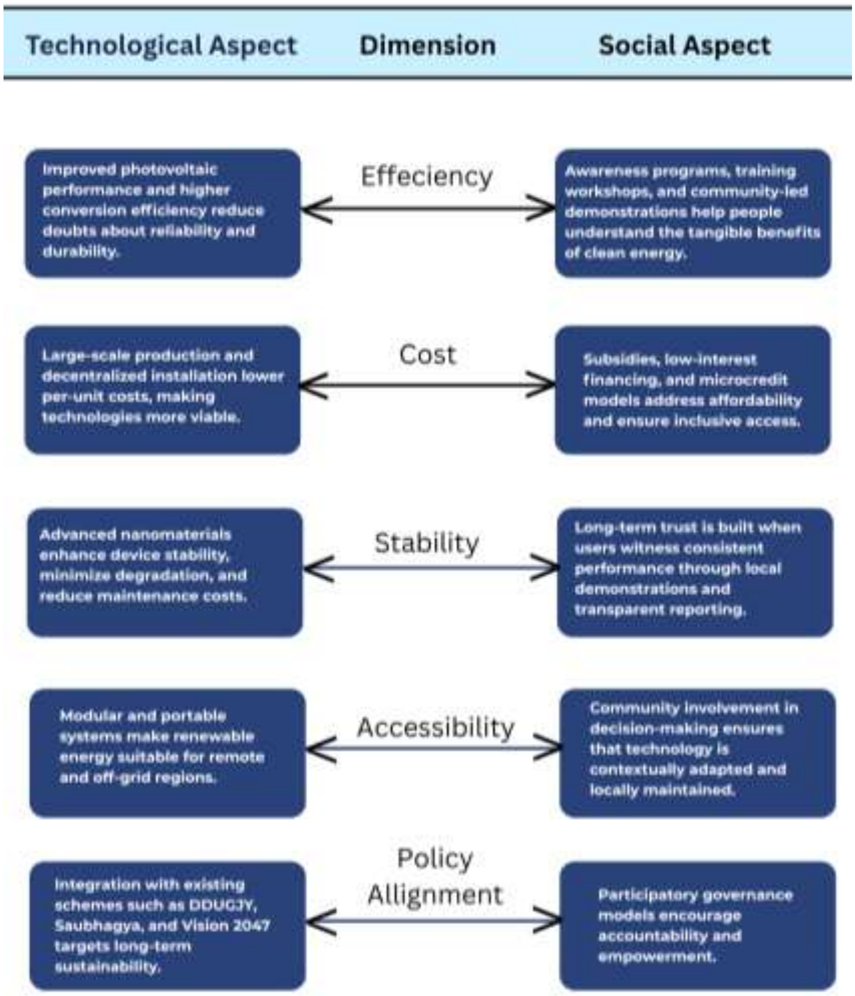


Figure 5 This diagram illustrates the relationship between technological and social aspects across five key dimensions for the implementation and sustainability of a technology, likely related to renewable energy

Through this dual-lens approach, STAF not only evaluates *what* makes a technology successful but also *how* that success can be socially sustained. It emphasizes that a purely technological solution—no matter how efficient—cannot transform lives unless it is socially acceptable, economically accessible, and institutionally supported.

The framework forecasts that, when technical innovations (like efficient nanostructures and stable coatings) are combined with social interventions (like awareness campaigns, subsidies, and participatory governance), the adoption of renewable energy solutions can rise by 15–20% in rural and semi-urban contexts.

By linking nanomaterial research with community-based energy planning, STAF offers policymakers a blueprint for bridging the persistent gap between technological innovation and social inclusion. It encourages a holistic understanding of energy transitions—where engineering excellence meets human aspiration—thereby contributing to India's long-term goals under Vision 2047 and its commitment to sustainable, equitable development.

4 Conclusion and Discussion

This review establishes a critical link between technological advancements in solar nanomaterials and their societal acceptance in rural India. The proposed Socio-Technical Acceptance Framework (STAF) bridges the gap between laboratory innovation and community integration by merging technical performance indicators with social and policy considerations. Findings from existing studies indicate that while nanomaterials—such as graphene, carbon nanotubes, and quantum dots—offer unprecedented efficiency improvements, their successful deployment in rural settings depends equally on awareness, affordability, and institutional trust.

The review also reveals that rural energy transitions are not merely a question of technology but of perception, participation, and policy alignment. Government initiatives under MNRE, NITI Aayog, and India Vision 2047 show promise but often lack integration between technical and social strategies. STAF demonstrates that combining awareness programs, local training, and financial incentives with scalable nanotechnology solutions could enhance adoption rates by 15–20%.

By emphasizing this dual approach, the study contributes to the discourse on sustainable energy transitions and highlights the need for an inclusive energy policy framework. Future research should test the STAF model empirically, exploring regional variations, gendered energy access, and long-term impacts on livelihood. Strengthening partnerships between academia, local governance, and private enterprises will be essential to translating solar nanotechnology from the laboratory to the field, ensuring equitable and lasting progress toward India's renewable energy goals.

5 Data Availability Statement

This study did not generate any new data. The analysis is based on existing literature from both technical and social aspects. All the references have been cited in the paper and can be accessed through the paper.

6 Funding Declaration Statement

No direct or indirect funding has been received from any source for the paper.

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