Research Article
The J. Res. PJTAU 54 (1&2) 69-75, 2026

BRIDGING THE ENERGY GAP THROUGH AGRICULTURAL EXTENSION: A REVIEW OF RENEWABLE ENERGY ADOPTION

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Date of Receipt: 08-01-2026 Date of Acceptance: 25-04-2026

ABSTRACT

India's renewable energy sector has undergone rapid transformation, emerging as a global leader in solar and wind capacity while pursuing energy self-reliance (Atmanirbhar Urja) through policy reform and domestic manufacturing. This review synthesises 20 research studies and government reports to examine how policy instruments, technological innovation, and agricultural extension have advanced renewable adoption in solar, wind, green hydrogen, and nuclear energy. Two case studies- Iran's carbon sequestration solar project and Karnataka's N. Kodihalli feeder solarization initiative, illustrate the role of extension services in driving adoption at the farmer level. Findings highlight persistent challenges in financing, grid integration, land acquisition, and regulatory readiness for emerging technologies. The study recommends equitable capital access, regulatory modernisation, and skill development to sustain India's ongoing energy transition.

Key Words: Renewable Energy Transition; Energy Self-Reliance (Atmanirbhar Urja); Agricultural Extension; Policy Reform; Green Hydrogen and Nuclear SMRs

In recent years, the use of fossil fuels has been identified as a significant contributor to environmental damage due to the emission of greenhouse gases (GHGs) that cause climate change. (IPCC,2023). Energy accessibility is universally acknowledged as a key catalyst for sustainable development and economic change. The United Nations Sustainable Development Goal 7 (SDG7) highlights the importance of ensuring that everyone has access to affordable, reliable, sustainable, and modern energy by 2030 (IEA, 2024; Qamruzzaman, 2025).

Over the past decade, India's energy landscape has undergone a transformation of historic scale and speed. From being a net importer heavily dependent on fossil fuels, the country has emerged as a global clean energy leader - ranking 4th globally in Renewable Energy (RE) Installed Capacity, 3rd in solar, 4th in wind, and holding the world's fastest-growing renewable energy program. The shift since 2014 is more than just about gigawatts added; it's about building an energy ecosystem that is secure, affordable, inclusive, and proudly self-reliant.(PIB, 2025)

Through bold policy reforms, targeted investment incentives, and rapid scale-up of domestic manufacturing, India is now laying the foundation for an Atmanirbhar Urja sector - one where every solar module, wind turbine, bio-pellet, and green hydrogen molecule increasingly comes from Indian soil, fuels Indian industry, and powers Indian homes.(PIB, 2025)

This paper presents a comprehensive review of the role of agricultural extension in renewable energy adoption, examining the progress made, the challenges encountered, and the opportunities available to accelerate the transition towards sustainable energy systems in agriculture.

Defining Energy Self-Reliance (Atmanirbhar Urja) and Its Necessity

Energy self-reliance in the Indian context refers to the process of reducing dependence on imported fossil fuels, building domestic manufacturing capacity across the solar, wind, and green hydrogen value chains, and diversifying the national energy mix toward renewable and non-fossil sources. When a nation achieves greater energy self-reliance, it improves its energy security, reduces foreign-exchange outflow on fuel imports, and moves closer to meeting its climate commitments under the Paris Agreement (Saryal, 2025).

This self-reliance is necessary to bridge India's historical import-dependence gap, support continued economic growth, and ensure a stable, affordable

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power supply for both industry and households. Without this transition, India remains exposed to import-price volatility, supply insecurity, and continued reliance on coal, which still supplies over 70% of the country's electricity even as renewable capacity grows (Pandey & Kumar, 2025).

India's shift toward renewable and non-fossil capacity enhances industrial competitiveness and long-term energy security, yet the scale of investment and regulatory reform this requires is often underestimated (Bhatia, 2023).

How Policy Reforms and Technology Facilitate India's Renewable Energy Transition?

Solar, wind, and green hydrogen technologies leverage declining costs, domestic manufacturing incentives, and digital monitoring and grid-integration tools to enhance capacity addition, cost competitiveness, and energy access across India's power sector. India's electricity transition remains fundamentally state-led, with government policy and control over key assets and incumbents shaping the pace of change more than market forces alone (Bhatia, 2023).

Policy reforms and technological tools play a crucial role in accelerating India's energy transition by addressing key challenges such as high upfront costs, grid-integration constraints, land-acquisition difficulties, and financing gaps. Systematic reviews of the coal phase-down process identify six recurring risks-threats to energy security, stranded assets, livelihood loss, technological complexity, import dependency, and fiscal losses- that continue to shape how policymakers design renewable-support instruments (Pandey & Kumar, 2025).

Additionally, dedicated policy analyses of India's National Green Hydrogen Mission show that its SWOT profile strong renewable resource endowment set against regulatory, storage, and demand-side uncertainties will determine whether India can meet its 2030 production targets (Sambasivam& Narayana Sarma, 2024).

However, financing and regulatory readiness remain major obstacles, particularly for emerging technologies such as offshore wind, where India's estimated potential exceeds 70 GW along its coastline but deployment remains nascent relative to onshore wind and solar (Rathinavel& Ramya, 2025). This gap is further widened by disparities in asset utilisation, cost competitiveness, and the social disruption that accompanies a shift away from a coal-dependent power sector (Debnath, Mittal, & Jindal, 2022).

Policymakers, private-sector stakeholders, and development institutions must collaborate to ensure inclusive, financeable technological advancement, bridging the financing divide and fostering equitable participation of states, developers, and communities in India's energy transition. Misunderstanding sub-sectoral financing needs and regional disparities in energy policy can lead to ineffective project planning and lower returns on investment (Bhatia, 2023). Keeping all this in view, this study has the following objectives.

Objectives of the Study

- To analyse the role of policy reforms and technological innovations (solar, wind, green hydrogen, and nuclear) in advancing India's transition toward energy self-reliance (Atmanirbhar Urja).
- To identify the key challenges and opportunities associated with scaling emerging renewable technologies, particularly offshore wind, green hydrogen, and nuclear small modular reactors, across India's energy sector.

MATERIAL AND METHODS

- In order to examine and synthesise prior research studies and official government data on India's renewable energy transition, the study takes a methodical and integrative approach, using an exploratory and descriptive research design. The study uses a qualitative research approach because it mostly uses secondary sources.
- A total of 20 research studies have been reviewed, covering various aspects of nuclear energy, solar energy, wind energy, and green hydrogen, along with the policy frameworks guiding India's shift toward energy independence (Atmanirbhar Urja).
- The data for this review was collected from scholarly databases such as Google Scholar and ResearchGate, using relevant keywords, including "India renewable energy transition," "green hydrogen mission India," and "nuclear energy policy India."

The selected literature includes research articles, review papers, and relevant scholarly sources that contribute to the study's objectives.

RESULTS AND DISCUSSION

(a) Enabling Access to Schemes and Information

Digital platforms such as the PM-Surya Ghar national portal help households and developers navigate subsidies and compliance with minimal friction (PIB, 2025). The shift from RPO to RCO obligations supports active consumption of renewable power, and Green Energy Open Access lets industrial consumers participate directly in the market (PIB, 2026). India's transition remains state-led, with policy design directly shaping adoption (Bhatia, 2023).

(b) Digital Monitoring and Grid Management

Tools like REEIMS and digital net-metering improve transparency and planning (PIB, 2026), but storage and grid-balancing technology adoption remains uneven due to cost and infrastructure gaps. Emerging efforts such as sodium-ion battery research and IoT-based plant monitoring are improving efficiency (PIB, 2026).

(c) Expanding Economic and Investment Opportunities

Record-low price discovery in green hydrogen/ ammonia auctions and signed offtake agreements have improved investor confidence (Sambasivam& Narayana Sarma, 2024). Solar manufacturing capacity has scaled nearly 75-fold since 2014 (Pandey & Kumar, 2025), and the sector has drawn nearly USD 45.72 billion in FDI (PIB, 2026) though nuclear and offshore wind still face large financing gaps (TERI, 2026).

(d) Strengthening Policy Coherence

Instruments like GTAM and VPPAs improve price discovery and planning certainty (PIB, 2026). Consolidating state RPO targets into a unified RCO framework has reduced compliance duplication (PIB, 2026); coordinated policy, not technology alone, has driven the pace of transition (Bhatia, 2023).

(e) Capacity Utilisation and Efficiency

Faster clearances and a dedicated wind Task Force are easing bottlenecks (PIB, 2026). Nuclear plant load factor reached 87% in FY 2024–25 even as capacity expands under the SHANTI Act (World Nuclear Association, 2026), reflecting efficiency gains alongside growth (Rathinavel& Ramya, 2025; Debnath, Mittal, & Jindal, 2022).

KEY INITIATIVES PROMOTING RENEWABLE ENERGY ADOPTION IN INDIA

PM-Surya Ghar: Muft Bijli Yojana: Provides subsidised rooftop solar installation for one crore households, with a national digital portal for application, feasibility, and subsidy disbursement (PIB, 2025).

PM-KUSUM: Supports farmers in solarising irrigation pumps and installing decentralised solar power plants, reducing diesel dependence and providing an additional income stream through surplus power sale (PIB, 2025; PIB, 2026a).

National Green Hydrogen Mission (NGHM): Provides manufacturing incentives, pilot projects, and certification standards to build a domestic green hydrogen ecosystem across hard-to-abate sectors like steel and refining (Sambasivam& Narayana Sarma, 2024; PIB, 2026a).

Model Solar Village Scheme: Introduces village-level solar capacity competitions, incentivising community-driven renewable adoption with a ¹ 1 crore prize for the top-performing village in each district (PIB, 2025).

Green Energy Open Access: Enables large consumers (e”100 kW) to directly access renewable power from generators through the grid, bypassing traditional discom-only procurement (PIB, 2025; Bhatia, 2023).

Vayumitra Skill Development Programme: Trains wind farm engineers and technicians to support the operations and maintenance needs of India's expanding wind sector (PIB, 2026a).

Jaiv-Urja Mitra Programme: Builds a skilled workforce of biomass aggregators, feedstock depot operators, and CBG technicians to support the bioenergy value chain (PIB, 2026a).

REEIMS (Renewable Energy Equipment Import Monitoring System): Enables real-time tracking of renewable equipment imports, ensuring supply-chain transparency and reducing dependence on non-domestic components (PIB, 2026a; Pandey & Kumar, 2025).

SHANTI Act, 2025: Opens India's nuclear sector to private-sector participation for the first time, enabling diversified investment models to help meet the 100 GW nuclear target by 2047 (World Nuclear Association, 2026; TERI, 2026)

Case Study: Role of Extension in Adopting Solar Energy - Carbon Sequestration Project, Iran

In 2003, Iran launched a carbon sequestration project in Hussain Abad, South Khorasan Province, covering 144,000 hectares near the Afghanistan border. Supported by UNDP and the Global Environmental Fund, the project aimed to reduce pasture degradation by promoting solar energy adoption through community participation, leveraging the region's high solar radiation potential (5 kWh/day). (Hosseini & Soltani, 2011)

A study surveyed 310 residents using solar energy for heating, analyzing satisfaction, knowledge, extension activities, and demographics via stepwise regression. Findings showed high satisfaction (4.39/5) and strong future interest (4.58/5) in solar energy. Contact with extension agents was the most valued method (4.21), followed by lectures and educational classes. Four factors-educational films/slides, extension agent contact, site visits, and lectures-explained 30% of variance in adoption perceptions.

Table 1. List of the Case Studies

Project Name	Carbon Sequestration Project – Solar Adoption (Hussain Abad, Iran)	N. Kodihalli Feeder Solarization (Karnataka, India)
Technology/Intervention & Audience	Solar heating systems for rural residents, supported by agricultural extension services	Feeder-level solar power plant (4.572 MW) for agricultural pump-set farmers (PM-KUSUM Component-C)
Objectives	Promote solar energy adoption to reduce pasture degradation through community participation	Provide reliable daytime electricity for irrigation; reduce agricultural power subsidy burden
Methodology	Survey of 310 residents; structured questionnaires; stepwise regression analysis	Technical feasibility study + pilot project implementation by CESC
Key Findings	High satisfaction (4.39/5) and future intent to use solar (4.58/5); extension contact, lectures, site visits, and educational films explained 30% of variance in adoption perception	Shifted farmers from night-time to daytime irrigation; improved water management, crop yield (especially sugarcane), labour use, and safety; reduced transmission losses and carbon emissions
Strengths	Strong extension-agent engagement; adaptable to local context; validated by comparable success in Bangladesh and Sri Lanka	Directly benefits 1,125 pump sets; replicable model already being scaled across Mandya district; strong environmental and economic co-benefits
Limitations	Only 30% of variance explained (many other factors unaccounted for); high illiteracy (44%) among respondents may limit reach of written/ educational materials	Requires significant land (~15 acres) and capital investment; benefits limited to farmers connected to the specific solarized feeder

The study concluded that solar adoption depends on timely information and active extension engagement, requiring location-specific strategies, echoing successful models in Bangladesh (Mondal, Kamp, & Pachova, 2010)and Sri Lanka. (Wijayatunga & Attalage, 2005)

Case Study: N. Kodihalli Feeder Solarization Project, Karnataka

Karnataka faces high agricultural power subsidy costs, heavy reliance on thermal generation, and strong daytime electricity demand from irrigation pump sets. Under PM-KUSUM Component-C, the state launched feeder solarization to generate clean power locally and supply it directly to farmers during daylight hours.

N. Kodihalli, near Besagarahalli in Maddur Taluk, Mandya district, was selected by CESC after feasibility studies confirmed proximity to the power distribution centre, availability of nearly 15 acres of suitable land, a large feeder base serving 1,125 pump sets, and strong daytime irrigation demand. The resulting 4.572 MW solar plant became Mandya district's first feeder solarization project under the scheme.

The project shifted farmers from unsafe night-time irrigation to flexible daytime power, improving water management, labor use, and safety -particularly benefiting sugarcane farmers through consistent soil moisture and support for drip/sprinkler irrigation. Beyond agriculture, it reduced carbon emissions and transmission losses, prompting CESC to replicate the model across Mandya as a scalable pilot for Karnataka's renewable energy future.(Gowda, 2026)

CHALLENGES IN SCALING RENEWABLE ENERGY ADOPTION IN INDIA

Financing Gaps: Emerging technologies such as offshore wind, green hydrogen, and nuclear SMRs face large financing shortfalls; reaching the 100 GW nuclear target by 2047 alone is estimated to require ¹ 23–25 lakh crore in additional investment (TERI, 2026).

Grid Integration and Land Constraints: Rapid renewable capacity addition has outpaced transmission infrastructure and land/right-of-way clearances, particularly in the wind sector, necessitating a dedicated Task Force to resolve bottlenecks (PIB, 2026a).

Continued Coal Dependency: Despite record renewable capacity growth, coal still supplies over 70% of India's electricity, and a full shift away from it is likely to take multiple decades due to a young thermal fleet and political lock-ins (Bhatia, 2023; Pandey & Kumar, 2025).

Import Dependence in Critical Components: Despite domestic manufacturing gains, India remains reliant on imported battery packs, solar glass components, and specialised parts, increasing exposure to global supply-chain disruptions (Pandey & Kumar, 2025).

Regulatory Readiness for New Technologies: India's nuclear regulatory framework was designed around large reactors, not small modular reactors, and existing rules under the SHANTI Act have not yet been fully notified (World Nuclear News, 2025) (World Nuclear Association, 2026; TERI, 2026).

Offshore Wind Underdevelopment: Only 1 GW of offshore wind capacity is currently backed by viability-gap funding, against a 37 GW bidding trajectory by 2030 - reflecting high capital intensity and nascent port/regulatory infrastructure (Rathinavel& Ramya, 2025).

Gap Between Installed Capacity and Actual Generation: Non-fossil sources supplied only around 29% of actual electricity generation in FY 2025-26 despite much faster growth in installed capacity, showing that capacity gains have not yet fully translated into displaced fossil generation (Pandey & Kumar, 2025).

Workforce and Technical Capacity Shortages: Scaling emerging sectors such as green hydrogen and offshore wind requires specialised technical skills that remain in short supply, despite recent skill-development programmes (Sambasivam& Narayana Sarma, 2024).

CONCLUSION

India's renewable energy sector plays a crucial role in the country's economic and strategic development, spanning solar, wind, hydro, bio-energy, green hydrogen, and nuclear power. However, challenges in financing, grid integration, land acquisition, and regulatory readiness often limit the pace at which installed capacity translates into actual displaced fossil generation. With evolving technology and policy support, India has achieved substantial capacity growth -crossing 288 GW of renewable capacity and climbing to third place globally - supported by reforms such as RPO-to-RCO consolidation, Green Energy Open Access, and GST rationalisation. These advancements provide developers, states, and consumers with access to vital price-discovery mechanisms, efficient grid management, and profitable investment opportunities, enabling more informed sectoral planning. By leveraging policy and technology together, India can strengthen its energy security and move closer to genuine self-reliance (Atmanirbhar Urja). However, barriers such as limited financing for emerging technologies, regulatory gaps, and workforce shortages persist. To address these challenges, there is a need for equitable capital access, regulatory modernisation, skill development, private-sector investment, and targeted institutional support to ensure India can fully realise the benefits of its ongoing energy transition.

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