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Energy Access to Livelihood Enhancement: Evaluating Solar Adoption in Rural and Tribal Communities

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Abstract

Access to reliable, affordable, and clean energy is increasingly recognized as a foundation of inclusive rural development. This study examines the adoption, determinants, and reported socio-economic impacts of solar energy among rural and tribal households in Raisen district of Madhya Pradesh, India. A mixed-method, cross-sectional design was used across 300 villages. Of 3,134 households contacted, 3,000 valid responses were included in the analysis. Quantitative data were collected through a structured Hindi-language household questionnaire and analyzed using descriptive statistics and binary logistic regression. Qualitative evidence was obtained through structured interviews, focus-group discussions, and field observations. A Socio-Economic Impact Index (SEII) was developed across four equally weighted dimensions: economic, social, environmental, and livelihood impacts.

The findings indicate that rooftop photovoltaic systems were the dominant technology, generally in the 1–3 kW range, while solar irrigation pumps were particularly relevant to farming households. Among adopters, 61% reported a reduction in monthly electricity expenditure, 24% reported increased income, and 70% perceived that solar expansion had generated direct or indirect employment opportunities in their communities. Social benefits included reported health improvements among 65% of respondents, while 76% perceived improved indoor air quality. Environmental outcomes included reduced dependence on firewood, kerosene, and other conventional fuels, reported by 42% of respondents. Peer influence, awareness of government subsidies, household income, and educational attainment were identified as positive determinants of adoption, whereas perceived installation cost was a negative determinant. Financial constraints, information gaps, inadequate technical support, and administrative complexity remained the principal barriers.

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Keywords: solar energy adoption; rural development; tribal communities; rooftop photovoltaics; solar irrigation; energy access; Raisen; Madhya Pradesh; India

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1. Introduction

Reliable energy access affects household welfare, agricultural productivity, education, healthcare, communication, and opportunities for paid work. In rural regions, the developmental value of electricity depends not only on physical connection to the grid but also on affordability, continuity of supply, and the capacity of households to use energy for productive and social purposes. Where electricity services are unreliable or unaffordable, households may continue to rely on firewood, kerosene, diesel, and agricultural residues. The World Health Organization identifies household air pollution from polluting fuels, including biomass and kerosene, as an important environmental-health concern [3].

India’s renewable-energy transition has created new possibilities for decentralized energy provision. Solar photovoltaics can generate electricity close to the point of consumption, reduce exposure to interruptions in centralized supply, and support household and agricultural applications. The policy environment includes the Grid Connected Rooftop Solar Programme, which seeks to expand grid-connected rooftop capacity and provides central financial assistance to eligible residential consumers [1]. In agriculture, the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyaan (PM-KUSUM) supports decentralized renewable-energy generation and solarization or installation of agricultural pumps, thereby linking energy policy with irrigation and farm economics [2].

The developmental effects of solar adoption, however, are not automatic. Households must be able to meet or finance the initial cost, understand the available technology and subsidy arrangements, obtain trustworthy installation and maintenance services, and perceive the system as reliable. These conditions are especially important in rural and tribal communities where incomes may be seasonal, information channels may be limited, and technical service providers may be distant. Adoption may therefore be shaped by a combination of economic capacity, education, policy awareness, social learning, perceived risk, and institutional accessibility.

This study investigates these relationships in Raisen district of Madhya Pradesh, a predominantly rural and agriculture-dependent setting with substantial tribal and socially disadvantaged populations. It addresses six questions: (1) What forms and patterns of solar adoption are observed among rural and tribal households. (2) What economic changes do adopters report? (3) What social and environmental outcomes are associated with adoption? (4) Which household and community characteristics influence adoption decisions? (5) What barriers limit wider adoption? and (6) What policy measures could make solar development more inclusive and durable?

The paper makes two contributions. First, it adopts a multidimensional perspective that treats solar energy as part of a broader rural livelihood transition rather than as a narrowly technical intervention. Second, it brings economic, social, environmental, and livelihood outcomes together in a proposed Socio-Economic Impact Index. The analysis also responds to the Sustainable Development Goals, particularly the interconnections among poverty reduction, health, education, gender equality, affordable and clean energy, decent work, and climate action [4].

2. Policy and Conceptual Context

2.1 Decentralized solar energy and rural development

Decentralized solar systems can affect rural development through several pathways. At the household level, generation of electricity can reduce expenditure on grid power or fuel-based lighting. At the productive level, electricity can lengthen operating hours, improve the reliability of small enterprises, and support information and communication technologies. At the agricultural level, solar pumps may reduce exposure to diesel prices and improve the timing of irrigation. At the social level, improved lighting and charging capacity can support study, communication, healthcare, and participation in public life.

These pathways are mutually reinforcing. Savings may be directed towards education or farm inputs; reliable electricity may enable a household enterprise; and a visible local installation may reduce uncertainty for neighboring households. Adoption can consequently generate community-level demonstration effects. At the same time, benefits may be unevenly distributed if the households most able to finance adoption are also the households most able to capture its benefits.

2.2 Adoption as a socio-institutional decision

A household’s decision to adopt solar energy can be conceptualized as a function of expected benefits, perceived costs, information, social influence, and institutional trust. Income affects the ability to finance the initial investment. Education may increase comprehension of technical and financial information. Awareness of subsidies can reduce the perceived price. Peer influence can reduce uncertainty by providing locally observable evidence of performance. Conversely, high perceived cost, uncertainty about maintenance, and complex subsidy procedures can discourage adoption even when households recognize the long-term benefits.

This conceptualization implies that policy must extend beyond capital subsidies. Financial assistance may be necessary but insufficient if households cannot obtain clear information, reliable vendors, after-sales service, or affordable credit. It also implies that social learning and local institutions—Panchayats, self-help groups, farmer organizations, schools, and community-based organizations—can play an important role in enabling adoption.

3. Materials and Methods

3.1 Study area and design

The study was conducted in Raisen district of Madhya Pradesh, India. The district was selected purposively because of its predominantly rural character, agriculture-based economy, presence of tribal and other socially disadvantaged communities, and relevance to the study of decentralized solar technologies. A mixed-method, cross-sectional household design was used. The quantitative component documented household characteristics, energy use, solar adoption, perceived outcomes, awareness, and policy preferences. The qualitative component explored experiences, barriers, community perceptions, and local implementation conditions.

3.2 Sampling and participants

The survey covered 300 villages selected from different administrative blocks to achieve geographical and socio-economic representation. A multistage sampling framework was used. Villages were selected purposively at the district and block levels, and households within selected villages were approached systematically. Both adopters and non-adopters were included so that adoption patterns and determinants could be examined comparatively. A total of 3,134 households were contacted, of which 3,000 valid responses were retained for analysis, representing a valid-response rate of approximately 95.7%.

Because the source summary does not report the number of households sampled per village or block, the distribution of adopters and non-adopters, or sampling weights, those details should be added in the final manuscript. The present draft therefore interprets the findings as descriptive and associational rather than as population-weighted causal estimates.

3.3 Data collection instrument and procedures

A structured questionnaire was prepared in Hindi and pilot-tested in selected villages. It included closed-ended and open-ended questions on demographic characteristics, social category, education, occupation, income, conventional energy use, solar technology ownership, installation characteristics, use patterns, awareness of government support, perceived economic and social outcomes, environmental changes, barriers, and policy preferences.

Primary data collection combined household surveys, structured interviews, focus-group discussions, and field observations. Field observations were used to verify reported solar installations and to document actual patterns of use. Secondary materials included government reports, Ministry of New and Renewable Energy publications, programme documents, census materials, and relevant research studies. Ethical procedures, informed consent arrangements, enumerator training, and institutional approval details are not specified in the executive summary and should be documented before submission.

3.4 Measures and analytical strategy

The primary dependent variable in the adoption analysis was binary solar-adoption status. The explanatory variables included household income, education, occupation, social category, awareness of subsidies, peer influence, age, and perceived installation cost. Descriptive analysis used frequencies, percentages, means, and cross-tabulations. Binary logistic regression was used to assess the association between household characteristics and adoption status. The source summary identifies the direction and relative importance of several predictors but does not provide coefficients, odds ratios, confidence intervals, model-fit statistics, or significance levels. These should be reported in a revised results table.

To capture broader developmental outcomes, the study developed a Socio-Economic Impact Index. The index comprised four dimensions: economic impact, social impact, environmental impact, and livelihood impact. Indicators included electricity-bill reduction, household savings, income enhancement, educational outcomes, healthcare improvements, reduced biomass use, improved air quality, agricultural productivity, and entrepreneurship development. Indicators were standardized to a 0–100 scale, equal weight was assigned to each dimension, and the resulting score was used to classify households into low-, moderate-, and high-impact categories.

The index can be represented as:

> ***SEII = 0.25Econ + 0.25Soc + 0.25Env + 0.25Liv****, where each component is a standardized dimension score on a 0–100 scale.*

The executive summary does not specify the normalization method, treatment of missing values, indicator direction, internal-consistency testing, or thresholds for the three impact categories. These methodological decisions should be stated explicitly and subjected to robustness checks in the final paper.

4. Results

4.1 Socio-economic profile of respondents

The sample included respondents from Scheduled Tribe, Scheduled Caste, Other Backward Class, and General social categories. Most respondents were in the economically active age group of 31–60 years. Men constituted a larger share of respondents, although women were important users and beneficiaries of household energy services. Educational attainment was concentrated at the primary and secondary levels, with comparatively limited higher education. The summary reports lower educational attainment among tribal households.

Agriculture was the dominant occupation, supplemented by livestock rearing, agricultural labour, wage work, self-employment, small business, and government service. Household incomes were generally modest, and tribal households were reported to have lower average incomes than non-tribal households. These characteristics are relevant because solar adoption requires an initial financial commitment even when subsidies are available, while the benefits may accrue gradually through lower operating costs and improved productivity.

4.2 Adoption patterns and technologies

Solar adoption was described as expanding across the study area, although adoption varied across villages and social groups. Rooftop solar photovoltaic systems were the most common technology. Most rooftop systems were in the 1–3 kW range and were used for lighting, fans, television, mobile charging, refrigeration, and other small appliances. Some households used solar electricity for productive activities, including tailoring, retail, small businesses, and agricultural operations.

Solar irrigation pumps were particularly relevant to farmers. The reported benefits included reduced diesel consumption, lower irrigation expenditure, improved access to water during critical crop stages, and more flexible irrigation scheduling. Grid-connected systems were more prevalent than off-grid systems. Respondents preferred grid-connected systems because of their perceived reliability and the possibility of net-metering, while off-grid systems were concentrated in locations with weaker grid service.

A substantial proportion of adopters reportedly installed their systems within the preceding three years. The summary attributes this momentum to declining technology costs, increased awareness, and government programmes such as the rooftop solar programme, PM-KUSUM, and PM Surya Ghar: Muft Bijli Yojana. The official rooftop programme provides central financial assistance to eligible residential consumers and channels applications through national or state portals [1]. PM-KUSUM similarly links solar deployment with decentralized generation and agricultural pump solarization [2].

4.3 Economic impacts

The most frequently reported economic outcome was a reduction in electricity expenditure. Approximately 61% of households reported a noticeable decline in their monthly electricity bills after adopting rooftop solar. Respondents indicated that savings were used for household needs, education, healthcare, food, agricultural inputs, livestock, irrigation equipment, and other improvements. These results suggest that solar adoption may improve financial resilience by lowering recurring energy expenditure, although the study does not report the absolute amount of savings or the payback period.

Approximately 24% of households reported an increase in income following solar adoption. Reliable electricity was associated with longer operating hours and improved performance of small shops, tailoring units, service enterprises, and home-based activities. Solar irrigation was also linked to lower operating costs and, in some cases, increased cropping intensity or cultivation of additional crops. Because the design is cross-sectional and the income outcome

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is self-reported, these findings should be interpreted as perceived or reported changes rather than verified causal income effects.

Employment and livelihood diversification were additional outcomes. Approximately 70% of respondents perceived that solar expansion had generated direct or indirect employment in installation, wiring, maintenance, repair, sales, distribution, and technical support. The study also observed emerging opportunities in food processing, digital services, agricultural processing, mobile charging, and other enterprises. These findings point to the importance of local service ecosystems: trained technicians and accessible repair networks may simultaneously improve system sustainability and create rural employment.

Economic outcome reported in the source study	**Reported share**	**Interpretation for this draft**
Noticeable reduction in monthly electricity bills	61%	Self-reported household cost reduction among respondents
Increase in household income after adoption	24%	Perceived or reported income enhancement; causal effect not established
Perceived employment opportunities from solar expansion	70%	Community perception of direct and indirect employment generation

4.4 Social impacts

The study associates solar adoption with improved educational conditions, healthcare, quality of life, women's empowerment, digital inclusion, and community participation. Reliable lighting reportedly allowed children to study for longer periods after dark and supported the use of mobile phones, televisions, computers, and internet-based learning resources. The executive summary does not provide measured changes in study hours, test results, attendance, or educational attainment; therefore, these findings should be presented as reported improvements in learning conditions.

Approximately 65% of respondents reported positive health outcomes after adopting solar technologies. The proposed mechanism was reduced reliance on kerosene lamps and biomass-based lighting, resulting in less smoke and soot indoors. Respondents associated cleaner air with fewer respiratory complaints and less eye irritation. Since health conditions were not clinically measured in the summary, the appropriate interpretation is perceived health improvement rather than a clinically verified reduction in disease.

Solar adoption was also linked to greater household comfort and security through improved lighting and appliance use. Women reportedly benefited from reduced drudgery, safer evening work, time savings, and opportunities for tailoring, food processing, handicrafts, and other home-based activities. Access to electricity also supported mobile connectivity, digital payments, government services, agricultural advisories, weather information, and health information. At the community level, improved lighting facilitated village meetings, awareness programmes, and social gatherings.

4.5 Environmental impacts

Approximately 42% of respondents reported reduced dependence on firewood, kerosene, and other conventional energy sources after adopting solar technologies. The reduction in fuelwood collection may ease pressure on local forest resources, while reduced kerosene use may lower indoor smoke and soot. Approximately 76% perceived an improvement in indoor air quality. These findings are consistent with the broader public-health rationale for reducing household exposure to polluting fuels [3], but the study does not provide direct measurements of particulate matter, fuel quantities, or greenhouse-gas emissions.

The environmental pathways identified by the study include reduced biomass use, lower fossil-fuel consumption, improved indoor air quality, conservation of forest resources, and increased awareness of renewable energy. Solar irrigation may additionally reduce diesel use in agriculture. The scale of climate benefits depends on system size, utilization, technology lifetime, electricity displaced, and end-of-life management; those parameters were not quantified in the executive summary and should be included in a future emissions assessment.

Environmental or health-related outcome	Reported share	Evidence type
Reduced dependence on firewood, kerosene, and conventional fuels	42%	Respondent report
Perceived improvement in indoor air quality	76%	Respondent perception
Positive health outcomes after adoption	65%	Respondent report; no clinical verification described

4.6 Determinants of Adoption

The logistic-regression analysis identified peer influence as the strongest reported determinant of solar adoption. Households were more likely to adopt when neighbors, relatives, or friends had installed systems and could demonstrate lower bills or improved services. This result emphasizes the importance of social learning in communities where households may be cautious about unfamiliar technologies.

Awareness of government subsidies was another important positive determinant. Respondents who knew about schemes such as PM Surya Ghar were more likely to adopt, suggesting that the effective cost of a programme depends partly on whether potential beneficiaries understand eligibility, application procedures, and expected support. Household income and educational attainment were also positively associated with adoption. Perceived installation cost was negatively associated with adoption, particularly among low-income and tribal households.

The results support a combined interpretation: adoption is shaped by both capacity and confidence. Income provides financial capacity; education and scheme awareness improve informational capacity; and peer influence builds confidence. High perceived cost undermines all three by making the investment appear risky or unattainable. The precise magnitude and statistical strength of these relationships cannot be evaluated until the full regression output is supplied.

4.7 Barriers

Financial constraint was the most prominent barrier. Even where subsidies were available, households faced an upfront contribution and competing demands related to education, health, food, agriculture, and daily consumption. Limited access to low-interest credit and irregular income further constrained adoption.

Information gaps affected knowledge of technologies, subsidies, financing, maintenance, and expected returns. Technical-support limitations included the shortage of trained installers, repair personnel, spare parts, and local service providers. Institutional barriers included complex documentation, uncertainty about eligibility, delays in subsidy approval, and slow disbursement. Finally, cultural caution and risk perception led some households to wait until neighboring households had accumulated experience.

5. Discussion

The findings indicate that solar adoption in Raisen is best understood as a multidimensional rural transition. The immediate benefit is a change in the household energy portfolio, but the consequences extend to farm operations, household finance, education, health, women's time, digital access, and community learning. The reported 61% reduction in electricity expenditure and 24% income-enhancement rate suggest that the economic value of solar is heterogeneous: savings may be widespread among adopters, while income gains depend on whether households have productive assets, enterprises, or agricultural opportunities that can use reliable electricity.

The importance of peer influence is theoretically and practically significant. Conventional subsidy-centred policy assumes that households make decisions based mainly on price. The Raisen findings suggest that social proof is also central. Model installations, transparent performance information, village demonstrations, and local adopters who can explain maintenance and billing may therefore produce effects that complement financial support. Community-level approaches may be especially useful in tribal and remote settlements, provided they are adapted to local institutions and languages.

The findings also demonstrate why adoption and impact should be assessed together. A household may adopt solar but experience limited economic benefit if the system is undersized, poorly maintained, or not connected to productive opportunities. Conversely, a modest system may generate meaningful welfare gains by improving lighting, charging, safety, and study conditions. The proposed SEII is useful because it recognizes these multiple pathways. Nevertheless, equal weighting is a normative choice, and the index should be tested for internal consistency, sensitivity to alternative weights, and differences between adopters and non-adopters.

The reported environmental effects are promising but should not be overstated. Replacing kerosene lighting with solar electricity can plausibly reduce indoor emissions, and replacing diesel pumping can reduce fuel use. However, rooftop solar electricity does not necessarily eliminate biomass used for cooking, and perceived air-quality improvements are not equivalent to measured reductions in particulate matter. Future research should distinguish among lighting fuels, cooking fuels, irrigation fuels, and grid electricity, and should quantify energy substitution directly.

The policy implications are consistent with the official design of India's decentralized solar programmes. The rooftop programme provides a structured route for residential financial assistance [1], while PM-KUSUM explicitly connects solar deployment with agricultural pumps and decentralized generation [2]. The challenge is implementation at the last mile. In Raisen, a more inclusive model would combine targeted subsidies, accessible credit, local-language outreach, village demonstrations, trained local technicians, and simplified administrative processes. Such an approach would address the financial, informational, technical, and institutional barriers identified by respondents.

6. Policy Implications and Recommendations

First, financial support should be differentiated according to household vulnerability rather than distributed as a uniform incentive. Enhanced assistance, interest subvention, installment payments, and group-based finance could improve access among low-income and tribal households. Self-help groups, rural banks, farmer organizations, and local cooperatives could serve as trusted intermediaries.

Second, outreach should be localized and demonstrative. Panchayats, schools, self-help groups, Farmer Producer Organizations, community radio, and local-language digital media can explain technology options, subsidy eligibility, application steps, net-metering, maintenance, and expected savings. Model solar villages and open performance records could use the strong peer effect identified in the study.

Third, local technical capacity should be developed. Training rural youth as installers and maintenance technicians would reduce downtime, lower service costs, and create employment. Village- or block-level service centres should maintain spare parts, provide repair contracts, and offer grievance redressal.

Fourth, solar deployment should be connected to productive-use programmes. Credit and enterprise support could prioritize solar-powered tailoring, food processing, cold storage, digital service centres, irrigation, and agricultural value addition. Women and tribal youth should be explicitly included in entrepreneurship and technical training.

Fifth, implementation systems should be simplified. A single-window process, transparent application tracking, clear eligibility guidance, time-bound subsidy disbursement, and coordination among government agencies, DISCOMs, banks, and vendors would reduce administrative uncertainty.

Finally, tribal areas require a dedicated inclusion strategy. Community-based systems, culturally appropriate communication, flexible finance, and integration with tribal-development, livelihood, and agricultural programmes can help ensure that solar expansion does not reproduce existing inequalities in access to capital and information.

7. Limitations and Requirements for Final Submission

This paper is drafted from an executive summary rather than a complete study report or dataset. Several limitations therefore require explicit attention before journal submission. The cross-sectional design does not establish causality or distinguish pre-existing differences between adopters and non-adopters. Many outcomes are self-reported perceptions rather than objectively measured changes. The sampling summary does not provide the village-wise or block-wise allocation, adopter/non-adopter counts, response rates by subgroup, or sampling weights. The regression summary omits coefficients, odds ratios, standard errors, confidence intervals, p-values, multicollinearity diagnostics, and model-fit statistics. The SEII description does not state the normalization procedure, missing-data treatment, reliability statistics, or category thresholds. The paper also requires documentation of ethical approval, informed consent, questionnaire items, enumerator training, and data-quality procedures.

These gaps do not invalidate the study's substantive contribution, but they limit the strength of claims that can responsibly be made. The final version should replace broad terms such as "significant impact" with "reported," "perceived," or "associated" wherever statistical evidence is not available. It should also include a full regression table, a sample-profile table with counts and percentages, a technology-adoption table, SEII summary statistics, and—if possible—comparisons between adopters and non-adopters using matched or multivariable methods.

8. Conclusion

Solar energy adoption in rural and tribal parts of Raisen district is associated with a broad set of reported economic, social, environmental, and livelihood benefits. Rooftop solar systems and solar irrigation pumps appear particularly relevant to household electricity needs and agriculture-based livelihoods. The study reports reductions in electricity expenditure, perceived income enhancement, employment opportunities, improved indoor air quality, positive health outcomes, and reduced dependence on traditional fuels. It also identifies peer influence, subsidy awareness, income, and education as important positive determinants, with perceived installation cost acting as a major constraint.

The central conclusion is that solar energy should be integrated into rural-development policy rather than treated as an isolated infrastructure intervention. Financial assistance must be accompanied by awareness, community demonstration, technical service provision, skill development, productive-use support, and special measures for tribal communities. If implemented inclusively, decentralized solar energy can contribute to energy security, livelihood resilience, human development, and environmental sustainability. The study's policy relevance is strengthened by its multidimensional perspective, while its scientific contribution will depend on completing the statistical and methodological reporting required for peer review.

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