

From Load Shedding to Energy Independence: Solar Energy and the Energy Transition in Punjab, Pakistan

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Abstract: Persistent electricity shortages and routine load shedding have long hindered social and economic development in Pakistan, with Punjab its most populous and industrialized province, bearing a disproportionate share of the burden. In recent years, however, solar power has emerged as a central pillar of provincial strategies to enhance energy security and reduce dependence on conventional, fossil-fuel-based generation. This paper examines how solar energy is contributing to Punjab's gradual shift from chronic load shedding toward greater energy independence. Adopting a qualitative, multiple-case design, the study draws on national and provincial policy documents, secondary reports, and peer-reviewed literature. It focuses on four key sectors: residential, agricultural, educational, and industrial, where solar initiatives have been promoted through programs such as free solar panel schemes for low-income households, school solarization, solar irrigation systems, and industrial rooftop installations. A comparative sectoral analysis evaluates these initiatives in terms of affordability, reliability, sustainability, and scalability. The findings show that solar energy has significantly improved supply reliability for many households and institutions, reduced operating costs for some farmers and industries, and opened new avenues for decentralized generation. At the same time, coverage remains uneven, key programs are still small relative to overall need, and implementation is constrained by financing barriers, bureaucratic delays, and limited technical capacity. The paper argues that Punjab's trajectory illustrates both the transformative potential and the persistent limitations of solar-led energy transitions in developing-country contexts. It concludes that scaling up equitable, decentralized solar adoption supported by robust provincial policies, innovative financing, and institutional reforms will be essential if solar power is to move from a complementary role to a structural driver of energy independence.

Keywords: Renewable Energies, Solar Power, Energy Transition, Energy Policy, Punjab, Pakistan.

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1. Introduction

Punjab, Pakistan's most populous and economically dynamic province, has historically suffered from frequent electricity shortages and extended periods of load shedding. For households, these outages translate into daily disruptions in lighting, cooling, and basic services; for farms and industries, they undermine productivity, damage equipment, and discourage investment. These problems are closely linked to national-level structural weaknesses in the power sector NEPRA's annual reports consistently document these trends in circular debt, capacity additions, and supply-demand imbalances across provinces (National Electric Power Regulatory Authority [1], including circular debt, aging

transmission and distribution infrastructure, and heavy dependence on imported fossil fuels.

At the same time, Punjab is endowed with high levels of solar irradiance, typically between 5.3 and 6.0 kWh/m² per day and over 300 sunny days annually. This natural advantage has spurred growing interest in solar power as a means to diversify the province's energy mix, improve reliability, and reduce exposure to fuel price volatility. In recent years, both the federal government and the Government of Punjab have introduced policies and programs designed to promote solar adoption at different scales, from utility-scale parks such as the Quaid-e-Azam Solar Park in Bahawalpur to household rooftop systems and solar irrigation schemes.

While these developments are frequently cited in policy documents and public discourse, there remains a limited understanding of how solar initiatives are actually reshaping energy use across different sectors of society in Punjab, and to what extent they contribute to what is often called "energy independence". In this paper, energy independence is not understood as complete separation from the national grid, but rather as a progressive reduction in structural dependence on centralized, fossil-fuel-based electricity through increased use of renewable and decentralized sources. This framing is in line with broader discussions that link renewable energy deployment and technological advances to long-term sustainable development goals [2]. This study addresses three main questions:

- (1) How is solar energy being adopted across key sectors in Punjab, particularly in residential, agricultural, educational, and industrial contexts?
- (2) How do national and provincial policies shape the design and implementation of solar programs in the province?
- (3) To what extent do these developments advance a more decentralized, resilient, and equitable energy system? By answering these questions, the paper seeks to contribute to the growing literature on energy transitions in Pakistan by providing provincial, cross-sectional data.

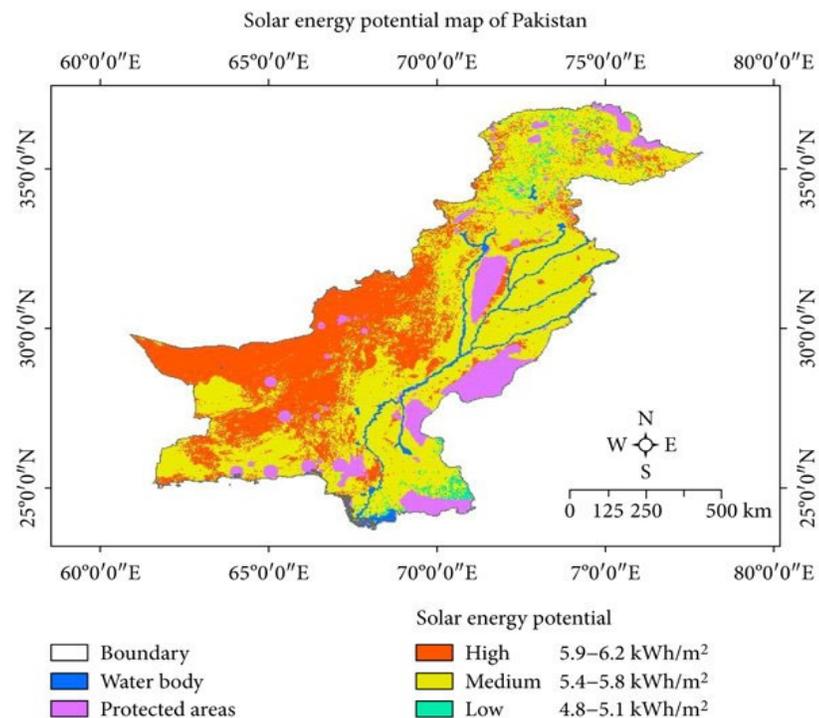


Figure 1. Solar Irradiance in Pakistan

2. Background of the Study

Pakistan's power sector has attracted sustained scholarly attention due to chronic supply-demand gaps, rising generation costs, and persistent governance challenges. Numerous studies highlight structural constraints such as circular debt, outdated transmission and distribution networks, high technical and commercial losses, and delayed capacity additions. Scenario analyses using tools such as LEAP show how different efficiency and fuel mix pathways could alter Pakistan's future energy demand and emissions, underscoring the importance of planning for long-term transitions [3]. These factors collectively erode the financial viability of utilities and undermine the reliability of electricity supply, particularly in high-demand regions like Punjab. Detailed modeling of domestic sector energy demand in Punjab shows how residential loads contribute to peak demand and how future consumption patterns may evolve in the absence of major efficiency or renewable interventions [4, 5].

A second strand of literature emphasizes Pakistan's substantial technical potential for renewable energy, especially solar. With high solar irradiance across most of the country, analysts argue that both small-scale and utility-scale solar deployment could play a significant role in addressing energy shortages and reducing dependence on imported fuels. International organizations such as the World Bank and IRENA, as well as domestic research institutions, have documented declining technology costs, the emergence of local installer markets, and a gradual increase in rooftop solar and net metering, particularly in urban areas of Punjab, where tariffs are relatively high, and grid reliability has often been inconsistent.

Policy-oriented studies focus on the evolution of Pakistan's renewable energy framework, with the Alternative and Renewable Energy Policy (2019) [6] frequently identified as a key milestone provincial strategy, including Punjab's renewable energy initiatives and solarization programs, which are framed as extensions of these national ambitions. However, the literature also notes that policy execution has been uneven, with bureaucratic delays, financing obstacles, and regulatory inconsistencies slowing the pace of change [7]. This policy sets national targets for increasing the share of renewables in the generation mix and introduces mechanisms to encourage private-sector participation. Provincial strategies, including Punjab's renewable energy initiatives and solarization programs, are framed as extensions of these national ambitions. However, the literature also notes that policy execution has been uneven, with bureaucratic delays, financing obstacles, and regulatory inconsistencies slowing the pace of change.

Another body of work looks at how renewable energy, and solar in particular, intersects with different sectors of the economy [8]. Studies on agriculture discuss the potential of solar irrigation to reduce farmers' fuel costs and enhance water security, while research on households and public institutions highlights the role of rooftop solar and backup systems in mitigating the impacts of load shedding. Complementary technical solutions such as home load management systems have also been proposed to ration demand during shortages and better align household consumption with constrained supply conditions [9]. Industrial analyses explore how firms use self-generation to manage energy costs and improve competitiveness. In Punjab's industrial sector, studies on brick kiln technologies highlight how energy-efficient and environmentally friendly upgrades can significantly reduce local pollution and fuel consumption, while facing adoption barriers related to finance and regulation [10].

Despite these contributions, several gaps remain. Much of the existing research is either national in scope or focused on specific technologies or projects, with relatively little attention to provincial-level dynamics and the ways in which different sectors within a single province experience the energy transition. There is also limited empirical work linking federal policies to concrete provincial initiatives and on-the-ground outcomes.

Finally, questions of equity, who benefits from solar adoption, in which locations, and under what financing arrangements are often underexplored. Studies on socio-demographic, psychological, and emotional determinants of household electricity saving behavior suggest that non-economic factors significantly influence how families respond to energy scarcity and efficiency opportunities [11]. This study addresses these gaps by offering a qualitative, cross-sectoral analysis of Punjab's solar transition and by explicitly examining the distributional and institutional dimensions of this process.

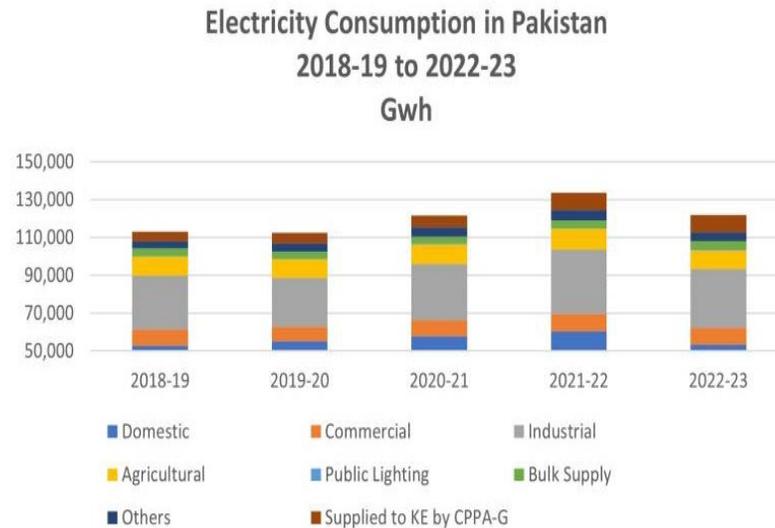


Figure 2. Energy Consumption Between Different Sectors [12]

3. Research Methodology

To investigate how solar energy is reshaping Punjab's shift from long-standing load shedding toward greater energy independence, this study adopts a qualitative, multiple-case design complemented by documentary and policy analysis. The focus is on understanding experiences, institutional arrangements, and context-specific implementation challenges rather than on producing precise quantitative estimates.

In this paper, "energy independence" is understood in a provincial and sectoral sense rather than as complete autarky from the national grid. The term refers to a progressive reduction in structural dependence on centralized, fossil-fuel-based electricity through the following:

- (a) An increased share of renewable electricity generation, particularly solar.
- (b) Expanded capacity for decentralized or distributed generation, such as rooftop systems and solar irrigation.
- (c) Improved resilience of households, institutions, and sectors to load shedding and price volatility. This working definition aligns with recent discussions on energy security and decentralized energy transitions in developing-country contexts.

3.1 Data Sources

The analysis draws on three main types of data. First, official policy and planning documents were reviewed, including national frameworks such as the Alternative and Renewable Energy Policy (2019), Punjab's renewable energy development plans, solarization programs, net metering regulations, and subsidy schemes, as well as regulatory documents from bodies such as NEPRA and the Ministry of Energy [1]. Second, secondary reports and grey literature were examined, including government reports, international and non-governmental organization publications, and reputable media coverage documenting

solar projects and initiatives in Punjab. Third, peer-reviewed academic literature was consulted to provide analytical and comparative insights on Pakistan's energy system, solar potential, policy implementation, and sectoral impacts.

These sources were selected because they offer complementary perspectives on policy intent, implementation experiences, and sectoral outcomes. Where possible, key quantitative figures such as the number of solarized schools, installed capacity, or budget allocations were cross-checked across at least two independent sources. In cases where only a single source was available, this is acknowledged, and the findings are treated as indicative rather than definitive.

3.2 Case Studies

The study employs a multiple embedded case study strategy focused on sectors that are central to Punjab's energy use and solar transition: the residential sector, the agricultural sector, the educational sector, and the industrial and commercial sector. Within each sector, illustrative initiatives or projects were identified that involve significant solar components, such as rooftop systems, solar irrigation, or institutional solarization.

A purposive sampling logic guided the selection of cases. To be included, a case had to be located in Punjab and explicitly involve solar energy adoption have been implemented for at least one year at the time of writing, allowing for observable outcomes be documented in at least two independent sources, a government report and an NGO or media report, or a policy document and an academic study provide sufficient detail on design, beneficiaries, scale, and preliminary effects. This process yielded a set of sectoral case vignettes, including free solar panel schemes for low-income households, solarization of public schools, solar tube-well programs, and rooftop installations in industrial estates.

3.3 Policy and Documentary Review

A systematic policy review was undertaken to understand the regulatory and institutional environment within which solar initiatives in Punjab operate. Key questions guiding this review included:

- (1) What targets and instruments are articulated in national policies regarding renewable energy deployment?
- (2) How are these targets translated into Punjab-specific programs and initiatives?
- (3) What evidence exists on implementation outcomes, bottlenecks, and equity implications?

The analysis covered national policies such as the Alternative and Renewable Energy Policy (2019), provincial program documents such as the Punjab Ujaala Program and solar subsidy schemes, and regulatory documents detailing licensing, tariffs, and grid-integration rules, including detailed tender and implementation documents for the Khadim e Punjab Ujaala Program on school solarization [13]. Insights from this policy review are integrated into the empirical sections to connect observed sectoral developments with the broader policy framework.

3.4 Comparative Sectoral Analysis

To capture how solar energy affects different parts of society, a cross-sector comparative analysis was conducted using four criteria drawn from the literature on energy transitions and energy justice: affordability, reliability, sustainability, and scalability. Documents and reports relating to each sectoral case were coded according to these dimensions and organized in a matrix that enabled comparison across sectors.

Affordability refers to both upfront and ongoing costs for users and the availability of subsidies, credit, or grant support. Reliability concerns the contribution of solar systems to

reducing outages and ensuring continuity of supply for key uses. Sustainability encompasses environmental benefits, the technical lifespan of systems, and requirements for maintenance and support. Scalability considers the potential to expand initiatives in terms of technical feasibility, institutional backing, and financial viability. The resulting qualitative assessment is summarized in a sectoral comparison that highlights strengths, constraints, and trade-offs in Punjab's solar transition.

3.5 Provincial Context and Data Limitations

A brief provincial comparison covering Punjab, Sindh, Balochistan, and Khyber Pakhtunkhwa (KPK) was included to contextualize Punjab's trajectory within Pakistan's broader renewable energy landscape. Drawing on national reports and academic sources, the comparison outlines each province's electricity demand profile and dominant or emerging renewable resources, such as wind in Sindh, hydropower in KP, and mixed solar, wind, and geothermal potential in Balochistan. This contextualization helps explain why solar energy plays a particularly central role in Punjab, which combines high demand with excellent solar irradiance but more limited large-scale hydropower or wind opportunities relative to some other provinces.

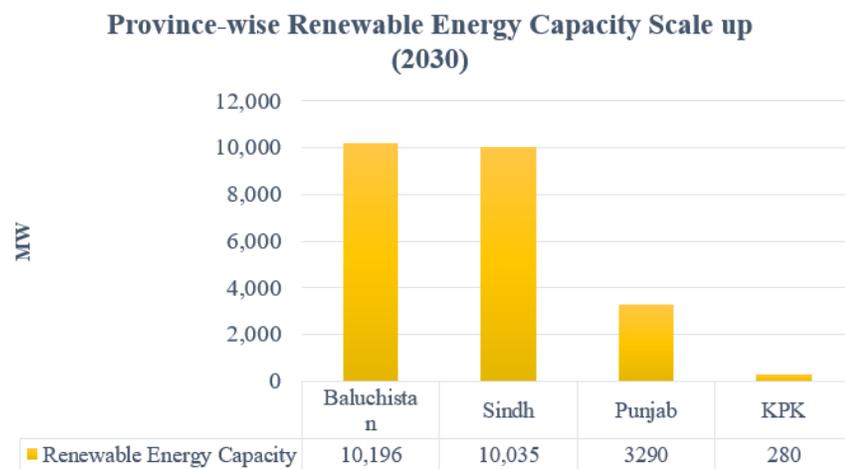


Figure 3. Energy potential Province Wise [14]

The study relies primarily on secondary data rather than original fieldwork, which imposes certain limitations. Reported figures sometimes differ across sources; where discrepancies were found, the analysis either used conservative estimates or triangulated information. Many programs are also relatively recent, so long-term impacts and sustainability cannot yet be fully assessed. Consequently, the findings should be understood as indicative of patterns and tendencies rather than as definitive measurements.

4. Provincial Energy Use and Renewable Potential in Pakistan

Understanding Punjab's solar transition requires situating it within Pakistan's diverse provincial energy landscape. Punjab accounts for the largest share of national electricity consumption due to its population, industrial base, and urban centers such as Lahore and Faisalabad. High demand, combined with historical reliance on centralized, fossil-fuel-based generation, has made the province particularly vulnerable to load shedding.

Sindh, by contrast, has lower overall demand but possesses significant wind resources, most notably in the Ghara–Jhimpir corridor, which has been the focus of large-scale wind power development. KP benefits from substantial hydropower potential due to its river systems and mountainous terrain, while Balochistan combines high solar radiation with dispersed wind and geothermal prospects. Together, these provincial endowments create a

diversified national renewable energy portfolio. These patterns are reflected in recent official statistics on provincial demand profiles and resource development [15].

Within this context, Punjab's comparative advantage lies in solar and, to some extent, biomass. The province's high irradiance and extensive rooftop and land surfaces make it well-suited to both distributed and utility-scale solar deployment. This provincial profile underpins the central argument of this paper: that solar energy is a particularly critical lever for enhancing energy security and reducing dependence on traditional sources in Punjab.

5. Findings

5.1 Residential Sector: Free Solar Panels and Rooftop Systems

In the residential sector, Punjab has pursued a dual trajectory of solar adoption. On one hand, relatively affluent households have increasingly invested in rooftop solar systems, often in combination with net metering. On the other hand, the provincial government has initiated targeted programs to support low-income households, most notably a 2024 scheme to provide free solar systems to 100,000 families.

The free solar panel initiative is explicitly designed to address affordability barriers for the poorest segments of the population. For beneficiary households, the program can significantly reduce electricity bills and enhance resilience to load shedding by ensuring a minimum level of power for lighting, fans, and basic appliances. However, relative to the total number of energy-poor households in Punjab, the program's scale is limited. Many low- and lower-middle-income families remain unable to finance rooftop systems, particularly in the absence of low-interest credit or pay-as-you-go models.



Figure 4. Rooftop Solar panels

For middle- and upper-income households, rooftop solar adoption has been driven primarily by high grid tariffs, frequent outages, and a desire for greater control over energy costs. Net metering has allowed some households to export surplus electricity to the grid, further improving the economics of investment. Yet procedural complexity and perceived bureaucratic hurdles continue to discourage others from participating, suggesting that regulatory design and implementation remain crucial determinants of uptake.

5.2 Educational Sector: Solarization of Schools

Under the Punjab Ujaala Program and related initiatives, more than 4,200 schools across approximately 25 districts have been equipped with solar systems, benefiting an estimated 600,000 students [16]. Higher secondary schools and special education institutions have also been prioritized, reflecting an effort to safeguard learning environments that are particularly sensitive to power disruptions.

Evidence from program reports indicates marked improvements in the reliability of electricity supply for these institutions. Solarized schools are better able to maintain

lighting, fans, and basic equipment during grid outages, which is especially important during examinations and in hot weather. From a sustainability perspective, the standardized design, centralized procurement, and planned maintenance arrangements of these systems increase the likelihood of long-term functionality compared to ad hoc installations.

However, coverage remains geographically uneven. Many schools in other districts still rely solely on grid electricity and remain vulnerable to load shedding. This raises equity concerns within Punjab's public education system, as some students benefit from improved energy services while others do not. The school solarization program thus exemplifies both the transformative potential of public-sector solar investments and the risk of intra-provincial disparities if expansion is not carefully planned and monitored.

5.3 Agricultural Sector: Solar Irrigation and Rural Applications

In Punjab's agricultural sector, solar-powered irrigation systems have gained traction as an alternative to diesel pumps and unreliable grid supply. Government and donor-supported programs have promoted solar tube-wells and subsidized systems for smallholders, highlighting their potential to reduce fuel costs and enhance water security. Evaluations of irrigation system performance in Punjab highlight how infrastructure management and water allocation practices affect both water and energy efficiency in agricultural production, underlining the importance of integrating irrigation reforms with solar irrigation programs [17].



Figure 5. Solar Powered Tubewell [18]

From an affordability standpoint, the high upfront cost of solar pumps remains a central challenge, particularly for small farmers without access to concessional credit. Where subsidies and soft loans are available, solar irrigation can significantly reduce operating expenses by cutting or eliminating diesel consumption. This is consistent with broader evidence that the economic viability of solar irrigation depends crucially on financing conditions and the relative prices of diesel and electricity. International case studies, such as cost-benefit analyses of photovoltaic irrigation systems in Honduran sugar cane production, similarly highlight how financing structures and fuel price dynamics determine the attractiveness of solar irrigation investments [19].

In terms of reliability, solar irrigation systems provide farmers with greater control over irrigation schedules and reduce dependence on grid availability and fuel markets. This can improve crop planning and resilience to outages. However, the scalability of these schemes is constrained by limited program budgets, technical capacity needs for system design, installation, and maintenance, and the absence of widespread advisory services. Without addressing these constraints, solar irrigation may remain a promising but unevenly distributed solution.

5.4 Industrial and Commercial Sector: Rooftop Solar for Energy Cost Management

Industrial and commercial users in Punjab have increasingly turned to rooftop solar as a strategy to manage energy costs and improve supply reliability. Large firms and industrial estates, in particular, have installed substantial rooftop capacity to hedge against high tariffs and frequent outages.

For these larger actors, solar investments can be financially attractive, especially when facilitated by net metering or other grid-interactive arrangements. Rooftop systems help stabilize energy expenditures and can enhance competitiveness by reducing exposure to tariff hikes and supply interruptions. In some cases, firms use solar as part of broader corporate sustainability strategies, signaling environmental responsibility to customers and investors.

Small and medium enterprises (SMEs), however, face more significant obstacles. High upfront costs, limited access to credit, lack of information about technical options, and uncertainty about regulatory stability can all deter investment. The result is an uneven industrial solar transition in which better-resourced firms move ahead while others lag behind, a pattern that echoes concerns in the literature that market-driven solar diffusion may reinforce existing inequalities in the absence of targeted support for smaller enterprises.

6. Discussion

The findings from Punjab corroborate several key themes in the literature on energy transitions in Pakistan while also extending them in new directions. They confirm that high solar irradiance, falling technology costs, and supportive policy frameworks create favorable conditions for decentralized solar adoption. However, integrating variable renewables into existing power systems also entails system-level costs related to balancing, grid reinforcement, and backup capacity, as emphasized by the System LCOE framework [20]. The expansion of rooftop systems, solar irrigation, and institutional solarization in Punjab illustrates how these factors translate into concrete projects across multiple sectors.

The analysis highlights the critical role of provincial governments in operationalizing national renewable energy policies. While the Alternative and Renewable Energy Policy (2019) sets broad targets and principles for increasing the share of renewables and enabling private participation [13], it is provincial initiatives such as free solar panel schemes, school solarization, and the promotion of net metering that shape the actual distribution of benefits and burdens on the ground. Punjab's experience demonstrates that proactive provincial leadership can partly compensate for national-level grid and governance constraints, particularly in the public sector.

The findings underscore that implementation bottlenecks remain a major obstacle to realizing the full potential of solar energy. Bureaucratic delays in net metering approvals, uneven outreach across districts, and limited local technical capacity all constrain the scale and equity of solar adoption. These challenges are consistent with broader critiques of policy execution in Pakistan's energy sector, which emphasize the importance of institutional capacity and coherent regulation. They also resonate with findings from integrated planning studies that highlight gaps between modelled transition pathways and on-the-ground policy follow-through [21].

Finally, the study adds to the emerging literature on energy justice and distributional outcomes in renewable energy transitions. In Punjab, benefits from solar adoption are unevenly distributed across income groups, sectors, and regions. Low-income households receive support only within the bounds of specific programs; many schools remain without solar despite high-profile solarization campaigns; and SMEs find it harder to invest in rooftop systems than large firms. These patterns suggest that without deliberate efforts to

address equity, the solar transition could replicate or even deepen existing social and spatial inequalities, even as it improves overall energy availability. This aligns with broader evidence that social and psychological factors shape who is able to adjust their energy practices and invest in new technologies [11].

7. Recommendations

Based on the analysis presented above, several policy directions emerge as priorities for deepening and broadening Punjab's solar transition:

1. Strengthen affordability mechanisms for low- and middle-income users. While free solar systems for selected households are important, they cover only a fraction of those affected by energy poverty. Complementary measures such as low-interest credit lines, on-bill financing, and community or cooperative solar models could help expand access to rooftop solar beyond current beneficiaries.
2. Expand solarization of public services in underserved districts. The positive impacts observed in solarized schools and health facilities suggest that scaling these programs to less-served areas could address spatial inequities while improving service continuity. Provincial authorities should prioritize districts with high levels of load shedding and limited alternative energy options.
3. Simplify and digitize net metering procedures. Making application processes more transparent, reducing processing times, and providing clear information to potential users would likely increase participation among households, SMEs, and institutions. Digital platforms for application tracking and standardized guidelines for distribution companies could reduce discretion and delays.
4. Invest in local technical capacity and after-sales services. Training programs for installers, technicians, and energy advisors, particularly in rural and semi-urban areas, would support the long-term sustainability of solar systems. Encouraging local entrepreneurship in installation and maintenance could generate employment while reinforcing the solar value chain.
5. Develop robust monitoring and evaluation systems for solar programs. Systematic data collection on the performance, distribution, and socio-economic impacts of solar initiatives would enable more evidence-based policy adjustments. Such systems should track not only installed capacity but also equity outcomes and user satisfaction.

8. Conclusion

Punjab's energy story is gradually shifting from one dominated by chronic load shedding and dependence on centralized, fossil-fuel-based electricity toward a more diversified and decentralized configuration in which solar power plays an increasingly important role. Through programs targeting households, farms, schools, and industries, solar energy has begun to improve reliability, reduce costs for some users, and open new possibilities for local generation.

At the same time, the transition remains partial and uneven. Solar initiatives are still small relative to overall demand, coverage is geographically and socially unequal, and implementation is hindered by financing barriers, regulatory complexity, and capacity constraints. Energy independence, in the sense of a substantial reduction in structural dependence on centralized conventional generation, is therefore a work in progress rather than an accomplished fact.

The analysis presented in this paper suggests that Punjab's experience offers valuable lessons for other provinces and countries seeking to leverage solar energy for energy security and development. It also reflects wider findings that strategic investment in

renewable energy and associated human capital can align energy security objectives with environmental sustainability.

It highlights the importance of provincial leadership, the need to align national policy frameworks with local implementation, and the centrality of equity considerations in designing renewable energy programs. Future research could build on this study through field-based work with households, farmers, and firms, as well as through more detailed modeling of how different policy and financing scenarios might accelerate or hinder the province's path toward sustainable and inclusive energy independence.

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