

Challenges and Opportunities in Rural Electrification: Analyzing the Impact of Off-Grid Renewable Energy Systems and Economic Factors in South Asia

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Research article

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Abstract

This study explores the relationship between electrification and energy accessibility in eight energy-poor South Asian countries (2000–2021) using the least-squares dummy variable (LSDV) approach. Findings reveal that while solar photovoltaics (SPV) initially show a positive impact on rural electricity (RUELEC), significance diminishes when accounting for specific country and year factors, likely due to external conditions like weather. This underscores the complexities of off-grid implementation in remote areas. However, Lewbel IV and three-stage least squares (3SLS) methods demonstrate SPV's stronger, independent impact, confirming its potential to empower rural communities. While economic growth generally boosts RUELEC, government effectiveness unexpectedly shows a negative correlation, possibly due to urban prioritization or regulatory barriers. Sensitivity analyses via PCSE and FGLS validate these results. The study concludes that SPV offers viable solutions for rural energy access, yet success requires addressing economic disparities, governance issues, and high infrastructure costs to ensure sustainable development..

Keywords: rural electrification; solar photovoltaics (SPV); off-grid renewable energy; energy access; government effectiveness; electrification challenges; least squares dummy variable (LSDV); renewable energy investment.

JEL Classification: Q42; Q48; O13; L94

Desafíos y oportunidades en la electrificación rural: análisis del impacto de los sistemas de energía renovable fuera de la red y de los factores económicos en el sur de Asia

Resumen

Este estudio explora la relación entre la electrificación y el acceso a la energía en ocho países del sur de Asia con pobreza energética (2000–2021), utilizando el enfoque de mínimos cuadrados con variables ficticias (LSDV). Los resultados revelan que, si bien la energía solar fotovoltaica (ESF) muestra inicialmente un impacto positivo en la electricidad rural, su significancia disminuye al considerar factores específicos del país y año, probablemente debido a condiciones climáticas externas. Esto subraya las complejidades de la implementación de sistemas fuera de la red en áreas remotas. Sin embargo, los métodos IV de Lewbel y mínimos cuadrados en tres etapas (3SLS) demuestran un impacto más fuerte e independiente de la ESF, confirmando su potencial para empoderar a las comunidades rurales. Mientras que el crecimiento económico generalmente impulsa el acceso rural, la efectividad gubernamental muestra inesperadamente una correlación negativa, posiblemente por la priorización urbana o barreras regulatorias. Los análisis de sensibilidad validan



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estos resultados. Se concluye que la ESF ofrece soluciones viables, pero el éxito requiere abordar las disparidades económicas, la gobernanza y los costos de infraestructura..

Palabras clave: electrificación rural; energía solar fotovoltaica; energía renovable fuera de la red; acceso a la energía; eficacia gubernamental; desafíos de la electrificación; mínimos cuadrados con variables ficticias (LSDV); inversión en energía renovable.

INTRODUCTION

In the next two decades, the developing world is expected to face a significant energy crisis (Billewar et al., 2023). Energy consumption in these regions is predicted to surge, primarily from fossil fuels (Aydin, 2015), which will likely intensify air pollution and increase greenhouse gas emissions. The global energy sector faces significant challenges, with approximately 1 billion people lacking access to electricity (Dey & Saha, 2025; Thompson, 2023). Despite the expansion of renewable energy sources, fossil fuels continue to dominate worldwide energy consumption, accounting for a sizable market share (Fornasiero & Graziani, 2012). This continued reliance on fossil fuels stymies a full transition to cleaner, more sustainable energy sources, underscoring the need to shift to renewable energy to meet global energy access and environmental goals.

South Asian countries have tremendous renewable energy potential, but implementing these resources is difficult due to a mix of socioeconomic reasons, technical constraints, and insufficient funding (Mitra et al., 2023; Poly et al., 2025). While hydropower dominates the renewable energy sector, solar and wind power remain underdeveloped, limiting the region's capacity to diversify its energy sources (Mitra et al., 2023). Existing investments in fossil fuel infrastructure, the high upfront costs of renewable technologies, and ongoing fossil fuel subsidies all contribute to delays in the transition to renewable electricity (Thompson, 2023). Despite these challenges, renewable energy is a critical potential for South Asia to achieve sustainable development, climate stability, and increased energy security (Kaygusuz, 2007; Thompson, 2023). A systematic shift in investment from fossil fuels to renewable energy is required to solve current issues such as poverty and climate change, while also generating long-term economic and environmental advantages (Kaygusuz, 2007; Thompson, 2023). By focusing on renewables, the region can ensure a more resilient, sustainable energy future while also contributing to global efforts to reduce climate impacts.

Rural electrification in South Asia has improved significantly, reaching 92.54 % in 2021, up from 55 % in 2001 (World Bank, 2022). Bangladesh, Bhutan, the Maldives, and Sri Lanka have achieved 100 % electrification, while India, Afghanistan, and Pakistan have rates of 94.4 %, 97.7 %, and 73.91 %, respectively (South Asia Source, 2023).

Since 2010, nations such as India, Bangladesh, Nepal, and Sri Lanka have achieved significant progress in electrification (Groh et al., 2023; Saha, 2025). Energy scarcity in Pakistan and Sri Lanka has reached a critical level due to persistent domestic challenges, underscoring regional distinctions in deep South Asia. As of 2023, more than 77 million people in the region remain without access to electricity, according to the International Energy Agency (IEA, 2023). Despite efforts to improve the situation, progress has been uneven, and Pakistan has struggled to effectively address the energy needs of its underserved population. Over 54 million people in Pakistan still lack access to electricity, reflecting limited advancements in energy access and infrastructure. These issues highlight the need for more robust policies and investments to bridge the energy gap, promote equitable development, and ensure sustainable energy solutions across the region.

In rural areas, access to electricity increases productive hours, allowing for evening activities such as farming and minimizing the limits of short daylight (Amuakwa-Mensah & Surry, 2022). More than 87 % of South Asian rural dwellers rely on agriculture for their livelihoods, with over two-thirds working in both agricultural and non-agricultural sectors (Rao et al., 2016).

Numerous studies show that rural electrification provides long-term benefits to rural communities by increasing agricultural productivity (Chaurey et al., 2004; Kanagawa & Nakata, 2008; Sackey & Nock, 2022; Saha, 2022; Saha & Saha, 2023) and expanding job opportunities, thereby helping reduce poverty in the long run. Agriculture, given its key role in rural economies, makes a considerable contribution to both employment and national gross domestic product (GDP; Ivanov & Sokolova, 2017).

Recognizing financial constraints and development inequities in rural South Asian nations necessitates rapid, radical change in rural areas. Energy availability is critical for promoting rural development and alleviating poverty, particularly in South Asia and Sub-Saharan Africa (Falchetta, 2021; Kaygusuz, 2011). Currently,

billions of people lack access to modern energy services, posing considerable challenges to achieving the Millennium Development Goals (Kaygusuz, 2011). To attract private energy investments, an integrated strategy is required that focuses on agricultural productivity and profitability. By 2025, energy demand in rural areas of developing countries is expected to exceed 4 TW, with biomass meeting most of the demand but requiring additional commercial energy inputs (Revelle, 1979).

Efforts under Sustainable Development Goal (SDG) 7 have advanced renewable energy projects to achieve universal energy access, contributing to broader SDGs. However, considerable obstacles remain. Progress toward the SDGs requires effort in four crucial areas: eliminating rural-urban gaps, linking energy access to long-term development outcomes, combining top-down and bottom-up approaches, and addressing techno-economic variables (Minas et al., 2024). Expanding energy availability has the potential to boost agricultural output (Amuakwa-Mensah & Surry, 2022; Rahman & Paatero, 2012) and raise the incomes of nonfarm workers (Sun et al., 2020). Demand for rural power in South Asia is expected to double by 2030, supporting irrigation and milling demands in neglected rainfed regions (Malik et al., 2017; Saha, 2023; Sun et al., 2020).

Electrifying isolated, economically disadvantaged rural places remains a serious problem. Expansion relies primarily on private investment, but low returns and high risks discourage it (Falchetta et al., 2021). Governments face limited resources to expand grid connections, while private entrepreneurs struggle to identify viable opportunities in decentralized systems (Qaiser, 2022). Traditional electrification efforts, such as those under SDG 7, have primarily targeted residential areas, but financial viability remains elusive. Recognizing this, several governments are turning their attention to rural electrification as a feasible solution. More than 4.1 million solar power systems have provided renewable electricity to approximately 22 million people (Dumitrescu et al., 2023). Solar power has improved family illumination, security, and education while decreasing reliance on hazardous energy sources (Era, 2024). The program, known as the world's largest off-grid solar venture, received USD 696 million in financing (Hellqvist, 2023), opening up new opportunities for infrastructure development (Saha, 2024).

Another recent example is the Indian government-funded effort in Maharashtra, which aims to address rural areas where centralized grid solutions

are problematic due to severe power shortages, distribution problems, and the fact that 5,554 villages remain without electricity. According to [Deshmukh \(2009\)](#), this project offers incentives to microfinance organizations to lend to business owners seeking to set up solar mini-grids.

South Asia is grappling with a critical energy dilemma, as more than two-thirds of its energy needs are met through imports, leaving the region highly vulnerable to global price fluctuations. These variations often lead to rising electricity costs, placing additional strain on economies and households ([World Bank, 2022](#)). The region's heavy reliance on fossil fuels further exacerbates the challenge, contributing significantly to greenhouse gas emissions and undermining global and regional efforts to combat climate change.

Frequent disruptions in energy markets have exposed the fragility of South Asia's energy systems, underscoring the urgent need for governments to secure reliable energy supplies. This situation presents a timely opportunity to shift toward renewable energy sources, particularly solar power. With its abundant sunlight, South Asia has immense potential to harness solar energy as a sustainable alternative. Expanding solar infrastructure can not only bolster energy security by reducing dependency on imported fuels but also mitigate environmental impacts by lowering emissions.

To realize this potential, coordinated policy initiatives, investments in renewable energy technologies, and regional collaboration are essential. By prioritizing solar energy development, South Asian countries can address their immediate energy challenges while advancing long-term goals of environmental sustainability and economic resilience. This transition is vital for achieving a more secure and sustainable energy future in the region.

Solar photovoltaics (SPV) appears to be a promising alternative for communities reliant on subsistence earnings in South Asian areas unlikely to receive grid access in the near future ([Irfan et al., 2019](#); [Sun et al., 2020](#)). Off-grid hybrid technologies powered by renewable energy have emerged as an increasingly viable alternative for electrifying the countryside in underdeveloped nations, aligning with global 2030 sustainability targets ([Ghafoor & Munir, 2015](#); [Mamaghani et al., 2016](#)). While substituting one fossil fuel for another may temporarily reduce costs, it fails to address the broader, long-term issues of fossil fuel depletion and climate change.

Renewable-based hybrid systems offer a sustainable alternative by ensuring energy access while mitigating environmental impacts. These systems represent a critical step toward reducing reliance on finite resources and advancing clean energy transitions in underserved regions.

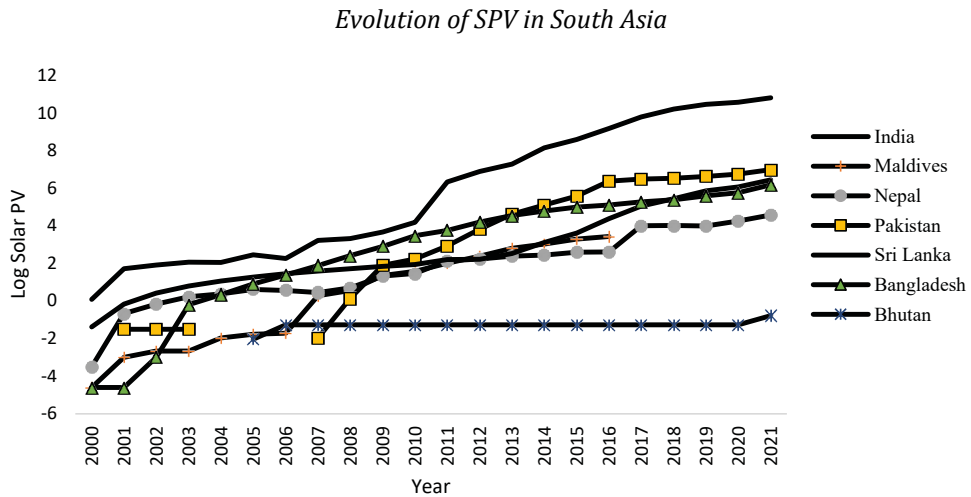
To achieve sustainability, new energy sources must compete with fossil fuels on availability and affordability, and be adaptable for use in both agricultural and non-agricultural contexts with modest modifications. Although SPV has limitations, such as issues with rural deployment and limited access for the poorest households due to funding constraints, successful support strategies should prioritize satisfying these households' needs and implementing affordability measures. Currently, this limits the use of SPV to remote areas and small-scale applications, reducing its competitiveness in powering industry and most cottage industries (Rady, 1992; Saha, 2025).

As shown in Figure 1, South Asia is experiencing a significant transition toward solar energy, with India leading the way. While solar adoption is increasing across all nations, growth rates vary: India and Bangladesh have experienced significant development, whilst Bhutan and the Maldives have progressed more slowly. The latter part of the timeline, particularly after 2015, highlights significant growth in SPV generation across South Asia. This surge reflects increased awareness of renewable energy's benefits and enhanced policy support to accelerate its adoption. Governments in the region have implemented various initiatives to promote solar energy, addressing both environmental concerns and energy security. These efforts align with global sustainability goals, driving investments in renewable technologies and infrastructure. Figure 2 illustrates the advancement of rural electricity (RUELEC) access in South Asian countries over 22 years (2000 to 2021), showcasing the expansion of energy access and the growing role of renewables in meeting the region's electricity needs.

Most countries have achieved considerable progress in RUELEC access, with India and Sri Lanka leading the way, while Afghanistan and Pakistan fall behind. India and Bangladesh show significant development, whereas productivity growth in the Maldives and Bhutan remains lower and slower.

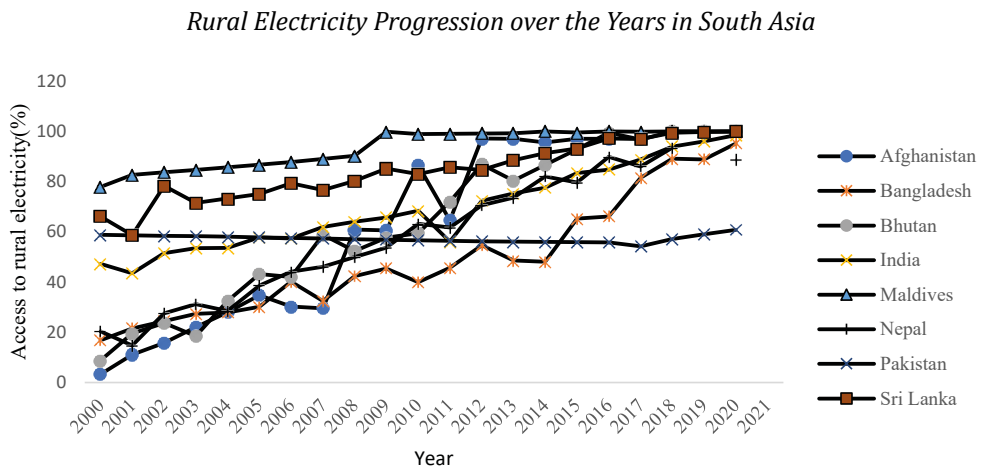
The United Nations has emphasized the crucial role of energy in achieving the SDGs (Casati et al., 2023). Despite the abundant solar resources in South Asian nations, the region's SPV potential remains untapped. With solar irradiation levels reaching nearly 2 MWh/m²/year, Pakistan is well-positioned to harness this resource

Figure 1.



Source: Own elaboration

Figure 2.



Source: Own elaboration

(Wakeel et al., 2016). Expanding SPV adoption in such regions not only addresses energy access challenges but also supports environmental sustainability and economic development through the integration of renewable energy.

The Asian Development Bank supports off-grid SPVs as an appropriate rural energy alternative due to their cost, ease of installation, and socioeconomic benefits. Research emphasizes its sustainability through net energy gains, cost-effectiveness (Sandwell et al., 2016), and better living standards (Mishra & Behera, 2016), without detrimental health implications (Hosenuzzaman et al., 2015; Shoron et al., 2025). This environmentally beneficial and cost-effective solution minimizes emissions and noise pollution (Akter et al., 2024; International Renewable Energy Agency [IRENA], 2019; Nasir et al., 2018). This makes it the ideal choice for RUELEC.

There is still a crucial gap in understanding how off-grid SPV could serve as a proxy for improved power availability and productivity in South Asia. While research examines the effects of rural electrification and the feasibility of SPV access, the precise relationship between the two remains unknown.

This study fills a knowledge gap by investigating the impact and sustainability of off-grid renewable energy options in rural South Asia. First, it examines how expanding off-grid SPV can improve electricity access in areas without grid connectivity. Second, it evaluates the overall impact of off-grid renewable energy systems such as solar, wind, and biomass on rural electrification. Finally, it examines how economic factors, such as prices, financing, and subsidies, contribute to the long-term viability of these off-grid energy options for rural populations.

The study also considers how SPV can improve electricity access in remote regions of South Asia, where approximately 60 % of the community resides. Inadequate accessibility to power stifles rural growth and transformation, hindering agricultural activities, non-farm small industries, and the sustainability of other subsistent wage earners. Access to electricity in the remote region benefits the local economy and the community's socio-economic transformation.

This study investigates how renewable energy, specifically SPV systems, can improve RUELEC in South Asia. This study uses advanced statistical methods, including least squares dummy variable (LSDV), feasible generalized least squares (FGLS), and instrumental variables-two-stage least squares (IV-2SLS), to analyze data from eight South Asian nations, addressing issues such as heterogeneity, autocorrelation, and potential endogeneity in the relationship between SPV and rural electrification. To tackle potential endogeneity among the explanatory variables, the research employs IV-2SLS techniques.

Moreover, this study contributes several distinctive novelties to the literature on rural electrification in South Asia. The contributions are divided into two parts: theoretical and empirical. Theoretical contributions include extending energy access theory by demonstrating that off-grid SPV does not operate in a vacuum—its effectiveness is contingent on governance quality, economic distribution, and environmental factors (e.g., weather). This challenges purely techno-centric models. This study also provides a contingency framework: the impact of renewable energy on rural development is moderated by government effectiveness (negative in this case) and income distribution—a nuance missing from most SDG7 literature. Empirical contributions are as follows:

- **Methodological Innovation:** It uniquely applies the LSDV approach alongside Lewbel IV and three-stage least squares (3SLS) methods to address endogeneity issues in off-grid SPV research—a methodological combination rarely employed in this context.
- **Counter-Intuitive Empirical Findings:** The study reveals three unexpected results that challenge conventional wisdom: (1) SPV's significance diminishes when accounting for country- and year-specific factors (particularly weather conditions), (2) government effectiveness shows a *negative* impact on rural electrification—likely due to urban bias or regulatory barriers, and (3) GDP per capita sometimes reverses its positive effect, suggesting unequal benefit distribution.
- **Underexplored Regional Focus:** While individual South Asian countries have been studied, this research provides a systematic 22-year panel analysis across *eight* energy-poor South Asian nations (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka), offering comparative insights rarely synthesized together.
- **Practical Policy Insight:** It identifies off-grid SPV as capable of bypassing governance constraints and infrastructure gaps, providing actionable evidence that decentralized renewable energy can succeed where government-led grid expansion faces institutional barriers.

LITERATURE REVIEW

Off-grid renewable energy solutions deliver clean, flexible electricity to women, youth, and entire communities in areas where the grid does not reach. By 2030, it is projected that over 60 % of newly electrified areas will rely on scalable solutions such as standalone systems and mini-grids, according to [IRENA \(2019\)](#).

Rural electrification has faced major financial hurdles and limited efficacy, imposing a significant financial burden on electric companies. Extending traditional grid connections to remote rural areas is often financially infeasible due to factors such as vast distances, difficult terrain, low projected energy demand, sparse populations, and widespread poverty. These challenges make it impractical to rely solely on conventional energy infrastructure. Furthermore, in areas with access to the electricity grid, the supply is frequently unreliable and of poor quality, making it unsuitable for approximately 20 % of communities that remain unelectrified ([United Nations Development Program \[UNDP\], 2000a](#)). This inadequacy has highlighted the limitations of conventional power systems in effectively meeting energy needs. Consequently, renewable energy sources are gaining recognition as practical and sustainable alternatives to bridge the energy gap. These sources not only offer a more reliable solution but also align with efforts to reduce environmental impacts and foster energy equity in underserved regions, paving the way for broader access to clean, efficient energy.

Off-grid and hybrid renewable energy systems provide an effective solution for delivering consistent, sustainable energy to underserved areas, addressing both access challenges and environmental concerns while fostering social and economic development in remote and marginalized regions.

Decentralized renewable energy (DCRE) generation is emerging as a promising solution for rural electrification, particularly in developing countries. DCRE offers potential to expand electricity access in remote areas where grid extension is challenging or infeasible ([Deichmann et al., 2010](#); [Kulkarni & Anil, 2014](#)). While DCRE can be cost-effective in certain rural and remote locations, grid-connected supply remains dominant in denser areas ([Deichmann et al., 2010](#)). The implementation of DCRE faces various challenges, including community perceptions, policy barriers, and the need for robust business models and maintenance systems ([Deshmukh, 2009](#)). Successful DCRE implementation requires overcoming socio-economic issues and increasing local participation ([Kulkarni & Anil, 2014](#)). Even small-scale

decentralized systems can significantly impact social and economic dynamics in rural areas, necessitating attention to potential conflicts of interest and points of friction (Ahlborg, 2015).

Bangladesh's performance with solar energy demonstrates the ability to achieve global energy goals. The rapid growth of its Solar Home System, currently valued at \$200 million, exemplifies how to achieve universal energy access and increase the share of renewable energy (Sharif & Mithila, 2013). Bangladesh is demonstrating its commitment to renewable energy by aiming to reach 40 GW of solar power by 2041 (Chowdhury, 2020).

Meanwhile, India's wind and solar energy potential of 1,730 GW by 2050 demonstrates the country's commitment to switching to renewable energy and reducing its dependency on fossil fuels (Chernyakhovskiy et al., 2021). This prediction accounts for India's enormous natural resources, good geographic conditions, and policy-driven emphasis on renewable energy production. The ambitious objective aligns with its climate goals under the Paris Agreement and with efforts such as the National Solar Mission. Achieving this capacity will greatly help India meet its expanding energy demands sustainably, improve energy security, reduce greenhouse gas emissions, and position itself as a global leader in renewable energy innovation and deployment. These countries show the way forward to a brighter, more sustainable future.

Nguyen's (2007) study looked at the role of renewable energy, specifically solar electricity, in Vietnam's energy economy. The study discovered that SPV technology could be a more cost-effective option for extending the central grid.

Kolhe et al. (2002) conducted an economic feasibility assessment of free-standing photovoltaic (PV) systems in India. The findings showed that when daily electricity demand exceeded 58 kilowatt-hours, PV systems became economically viable compared to diesel generators. This proved PV systems' promise as a sustainable, cost-effective energy option for areas with high energy demand.

The study by Bugaje (1999) in Nigeria compared several energy options, including grid extension, decentralized solar power, and diesel generators. The study discovered that solar power plants are best suited for sites within 50 kilometers due to their efficiency and feasibility. Similarly, solar energy's economic viability

in off-grid areas of Bangladesh demonstrates its ability to sustainably meet energy needs where grid access is difficult or unavailable (Bhuiyan et al., 2000).

These findings are consistent with successful solar installations in Southeast Asia and Sub-Saharan Africa, where solar power systems have boosted rural development, increased household incomes, created jobs, and contributed to overall socioeconomic advancement.

RESEARCH GAP

While existing studies confirm that rural electrification improves livelihoods and that SPV is technically feasible in South Asia, they suffer from three major limitations: (1) most are single-country case studies (Bangladesh, India, Pakistan) with limited generalizability; (2) they rarely account for endogeneity between SPV adoption and electricity access; (3) no study has systematically examined how time-varying external factors (e.g., weather variability, political shocks) and government effectiveness alter the impact of off-grid SPV across the entire region. Therefore, the relationship between off-grid SPV and rural electrification remains empirically inconclusive and context-dependent—a gap this study addresses by using panel data and advanced econometric techniques that isolate causal effects while controlling for unobserved heterogeneity.

COMPONENTS AND APPROACHES

Estimation Method

This study uses yearly panel data, merging state-level and yearly data to improve analysis accuracy and capture various forms of variability. To begin, the stationarity of the variables was examined using descriptive statistics and panel unit root tests, following the methods of Im et al. (2003). Subsequently, pre-estimation checks were conducted on the heterogeneous panel data using Pedroni's (2007) cointegration tests. Cointegration was determined by comparing p -values to the 5 % significance level.

This study examines the interrelationship of rural electrification and solar energy across eight South Asian countries over a 20-year period. These countries, despite their geographic proximity, exhibit diverse economic structures, government systems, and

levels of development, ranging from India and the Maldives to Afghanistan and Nepal. Previous research has established a link between rural development and economic growth, particularly in reducing poverty. Given these inter-country variations, we expect the relationship between the variables to differ across nations.

To account for differences among countries, we used the LSDV methodology. This method allows us to analyze data from multiple countries over time while considering each country's unique characteristics. By using this method, we can obtain more accurate results. The LSDV method, suitable for our panel data with a reasonable time span and only a handful of countries, effectively addresses endogeneity arising from time-invariant heterogeneity (Bun & Kiviet, 2006).

In many circumstances, researchers are particularly interested in the long-term effects and how quickly a system adjusts to these consequences. Our research focuses on the long-term implications of RUELEC availability on off-grid renewable energy sources. We prioritize studying long-term repercussions above short-term dynamics. Consequently, the LSDV technique was the best analytical strategy for our study.

The estimation approach for this objective may adopt the shape mentioned in Equation 1:

$$Y_{it} = \xi + \eta Z_{it} + \delta_i + \alpha_t + \rho_{it} \quad (1)$$

In this equation, α_t represents changes over time, δ_i represents differences between countries, Z_{it} represents other factors that influence the outcome, t represents time periods, and i represents individual countries. The primary goal is to obtain a reliable estimate of η that meets all necessary criteria.

Previous research on rural electrification and off-grid SPV installations has raised concerns about reverse causality. To address potential bias in our analysis, we used the Lewbel (2012) instrumental variable (IV) method. This method helps us obtain more accurate and reliable results.

Endogeneity Checks Using the 2SLS-IV Approach

Initially, we used the LSDV method. To address endogeneity, we employed an IV technique developed by Lewbel (2012). To overcome these limitations, we employed

an IV technique. This technique requires specific statistical tools that are often difficult to find. Therefore, we used Lewbel's 2SLS method, which is especially useful when these tools are unavailable. This method has been used successfully in many previous studies.

Our study included eight nations. To establish a clear cause-and-effect relationship, we adjusted the dependent variable to reflect the consequence of past SPV installations on current outcomes. To improve the accuracy of our analysis, we also adjusted certain variables to better fit our statistical model.

3SLS Methodology

This study employs the 3SLS method to address several critical issues and investigate the complex relationship between SPV and power accessibility in South Asia. One important reason is to account for simultaneity bias and endogeneity, as SPV affects rural electrification while power access may potentially influence SPV adoption. 3SLS can estimate many connected equations, such as those affecting rural electrification, economic growth, and government effectiveness, making it better suited to modeling these dynamics than single-equation approaches. Furthermore, 3SLS is more efficient when the error terms across equations are correlated, yielding more precise estimates. It also aids in resolving IV issues by using factors such as government policy or weather conditions as instruments for endogeneity correction. The technique corrects for measurement inaccuracies by combining data from related equations, and its ability to handle complex policy and economic connections makes it ideal for modeling the multiple relationships between SPV and rural electrification. Overall, 3SLS increases the trustworthiness of the results by resolving these difficulties.

Therefore, the justification for each method is as follows:

- LSDV is chosen because our panel has a moderate time dimension ($T = 22$) and a small cross-section ($N = 8$). LSDV effectively controls for unobserved country-specific, time-invariant heterogeneity (e.g., geography, culture) that could bias results, while allowing us to estimate long-term relationships rather than short-run dynamics.
- Lewbel IV is used because valid external instruments are notoriously difficult to find for energy access studies. Lewbel's approach generates internal instruments from heteroskedasticity in the error terms, providing

consistent estimates when traditional instruments are weak or unavailable. Thus, the Hansen J overidentification test (p -value = 0.342) and the first-stage F -statistic ($F = 28.6 > 10$) are also reported, confirming instrument relevance and validity.

- 3SLS is employed because rural electrification, economic growth, and government effectiveness are simultaneously determined. 3SLS estimates all equations together, accounting for cross-equation error correlation, which is more efficient than 2SLS. The Breusch-Pagan test for contemporaneous correlation is administered ($\chi^2 = 47.3, p < 0.001$), which justifies the use of 3SLS over single-equation methods.

Moreover, a few other tests are also administered. Multicollinearity is checked using the variance inflation factor (VIF), where all values are less than 5 (mean VIF = 2.3), indicating no problematic collinearity; the Hausman test is measured for fixed vs. random effects ($\chi^2 = 42.1, p < 0.001$), justifying country-fixed effects; the Wooldridge test for autocorrelation found that $F = 23.4, p < 0.01$, confirming serial correlation, which our panel-corrected standard errors (PCSE) and FGLS robustness checks address.

Econometric Specifications and Data Calculations

This study examines the effects of rural electrification on SPV system adoption in eight South Asian nations over 22 years (2000 to 2021). It provides a broad regional perspective by examining SPV adoption patterns despite limited data availability. The chosen timeframe corresponds to the period during which trustworthy data could be sourced. The study examines the relationship between rural electrification efforts and increased reliance on solar energy, shedding light on how access to electricity has influenced renewable energy adoption across countries and with implications for future energy strategies. Key variables, their definitions, and sources are listed in [Table 1](#), while descriptive statistics and correlations are presented in [Tables 2](#) and [3](#), respectively.

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Table 1.

<i>Defining Variables and Data Sources</i>			
Variable	Definition	Measure	Source
SPV	Installation of SPV units	In megawatts	IRENA ¹ (2023)
RUELEC	Electricity accessibility	The proportion of rural residents with access to a grid-based energy source in a nation	WDI ² (2024)
GDPPC	Income intensity (GDP per capita)	Measured by PPP ³ and constant (2017)	WDI ² (2024)
GOVTEFF	Government effectiveness	This indicator ranges from -2.5 (lower effectiveness) to 2.5 (higher effectiveness)	WGI ⁴ (2024)
INST	Institutional quality ⁵	The Productive Capacity Index (PCI) is a measure of institutional quality. A higher PCI score indicates a stronger institutional framework, characterized by effective governance, the rule of law, and protection of property rights. Conversely, a lower PCI score suggests weaker institutions and a less favorable business environment	UNCTAD ⁶ (2022)
RUPOP	Rural population	Proportion of rural population as a % of total population	WDI ² (2024)

Note. ¹ International Renewable Energy Agency; ² World Development Indicator; ³ Purchasing power parity; ⁴ World Governance Indicator; ⁵ Institutions examine political stability and performance by assessing regulatory bodies, law enforcement effectiveness, control over corruption, anti-terrorism measures, and protection of civil liberties; ⁶ United Nations Conference on Trade and Development.

Source: Own elaboration

Table 2.

<i>Summary Statistics</i>					
Variable	Observations	Mean	Standard deviation	Minimum	Maximum
LnSPV	152	2.250111	3.249899	-4.60517	10.80652
LnRUELEC	163	20.76985	2.621724	15.16422	25.21719
LnGDPPC	174	8.515909	0.714856	7.138915	9.931803
GOVTEFF	168	-0.42061	0.60907	-2.17395	0.872711
INST	152	41.62944	12.67121	10.64	63.979
RUPOP	176	16.69	2.606485	12.22293	20.62828

Source: Own elaboration

Table 3.

Correlation Results						
	SPV	RUELEC	GDPPC	GOVTEFF	INST	RUPOP
SPV	0.66*					
RUELEC	0.66*	1.00				
GDPPC	-0.02	-0.48*	1.00			
GOVTEFF	-0.10	-0.34*	0.71*	1.00		
INST	-0.15*	-0.38*	0.70*	0.95*	1.00	
RUPOP	0.13*	-0.45*	0.63*	0.80*	0.73	1.00

Note. Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

The model can be written as follows (Equation 2), which investigates the factors impacting energy access:

$$\ln RELEC_{it+1} = \lambda_0 + \lambda_1 \ln SPV_{it} + \lambda_2 RUPOP_{it} + \lambda_3 \ln GDPPC_{it} + \lambda_4 GOVTEFF_{it} + \lambda_5 INST_{it} + \lambda_6 Year + \lambda_7 FE_{id} + u_{it} \quad (2)$$

Access to electricity is vital for rural people. This includes grid- and off-grid energy options.

To understand the complex effect of rural electrification on off-grid SPV, we examine several influencing factors identified in previous research. A key variable in this analysis is the number of SPV units installed off-grid, which represents technological advancement. This variable, measured in megawatts by IRENA, reflects the peak power-generation capacity of solar installations. We prioritize installment coverage as the primary indicator, as it better indicates the increase in energy supply relative to investment levels.

Power generation is controlled by consumption levels and does not immediately incorporate possible gains in power access, which is the primary emphasis of this research. The primary variable of interest in this study is SPV, which serves as the dominant supplement to grid power in South Asia (Chernyakhovskiy et al., 2021). Access to clean and affordable energy is particularly important for small farmers, who often live in areas without reliable grid electricity (Rahman et al., 2022). This energy access is essential for sustainable economic and social development (Ayana & Degaga, 2022; Saha, 2025; Şaşmaz et al., 2020). PV technology stands out as a cost-effective choice, particularly for supplying electricity in off-grid, low-demand

areas (UNDP, 2000b). PV technology can help rural communities progress by providing essential services, such as residential illumination, transistor radios, and refrigerators for medication storage in rural clinics. SPV is projected to have a positive and statistically significant influence on RUELEC access ($\lambda_1 > 0$).

Providing inexpensive, sustainable electricity to rural communities has the potential to significantly improve economic and social outcomes (Balachandra, 2011; Olanrele, 2020; UNDP, 2000a). Electricity is the most effective and easily accessible source of energy, particularly for rural families and small businesses in developing countries (UNDP, 2000a). In these locations, where poverty is concentrated in rural villages, energy availability is intimately linked to socioeconomic advancement, higher living standards, and better educational performance (Abbas et al., 2020). Although many people cannot afford energy, research shows that power demand is rather income-inelastic (Mainali et al., 2014). Consequently, the proportion of the rural population (RUPOP) is positively correlated with energy access, implying a direct impact ($\lambda_2 > 0$).

GDP per capita, measured in purchasing power parity (PPP) in US dollars, is calculated by dividing a country's GDP by its total population. An increase in GDP per capita indicates rising individual income levels, which often leads to higher demand for goods and services. This heightened demand stimulates domestic production and improves labor productivity, contributing to overall economic growth (Wonyra & Ametoglo, 2020).

Beyond its role as an economic metric, GDP per capita also reflects broader economic development. It signifies higher economic activity, greater social mobility, and more employment opportunities. These improvements collectively drive the need for reliable energy access, as energy becomes a critical enabler of sustained growth. SPV systems offer a viable solution to meet this rising energy demand, providing scalable, sustainable energy. The positive relationship between GDP per capita and SPV adoption ($\lambda_3 > 0$) suggests that as economies grow and incomes rise, the demand for renewable energy solutions like SPV will also expand. This makes GDP per capita not only a key economic indicator but also a significant driver of energy transitions, particularly in regions aiming for sustainable and inclusive development.

The World Bank's government effectiveness indicator measures how well a government functions, including the quality of public services, the efficiency of government workers, and the government's commitment to its policies (Duho et al., 2020). Based on expert assessments, it uses stakeholder surveys to

rate governance on a scale from -2.5 (least effective) to 2.5 (most effective), providing a comprehensive picture of governance quality in a given country. Effective governance is characterized by the ability to design and implement clear, consistent policies that promote investment in power facilities, strengthen local capacities, and manage energy pricing to keep it affordable (Miskiewicz, 2022). This promotes community-driven energy resource management and enables collaborations with corporate and international groups to increase access. However, even with good intentions, political constraints, competing objectives, and limited financing can all provide obstacles for governments (Ampaire et al., 2017). Weak environmental rules and a lack of attention to renewable energy can lead to detrimental activities that exacerbate climate change (Helm, 2010). λ_4 may take positive or negative values, depending on governance outcomes.

RESULTS AND DISCUSSION

Preliminary Analysis: Estimated Findings on the Impact of Off-Grid SPV Systems on Electricity Access in Rural Areas of South Asian Countries

Descriptive Statistics

The summary statistics presented in Table 2 provide insights into the characteristics of the key variables analyzed in the study, while the correlation results are presented in Table 3. The average adoption of SPV systems (mean = 2.25) is relatively low, with a high standard deviation ($SD = 3.25$), indicating significant variability across observations. The range indicates that while some areas have significant capacity (high positive logs), others have very small installations (negative logs representing less than 1 MW), showing disparity in adoption levels. The mean RUELEC (20.77) indicates moderate levels of rural electrification, with relatively low variability ($SD = 2.62$). The minimum value (15.16) implies limited access to electricity in some areas, while the maximum (25.22) reflects better rural connectivity in others, showing room for improvement in underserved regions.

The average GDP per capita (mean = 8.52) is relatively uniform ($SD = 0.71$), suggesting consistent economic performance across regions. A minimum of 7.14 and a maximum of 9.93 highlight a moderate disparity, with implications for income-driven energy demands and SPV adoption. The negative mean indicates overall weak institutional performance, with variability ($SD = 0.61$) across observations. The range

(-2.17 to 0.87) suggests significant governance challenges that could hinder energy access and development initiatives. Institutional quality scores show moderate effectiveness, with high variability ($SD = 12.67$). The wide range (10.64 to 63.98) reflects disparity in institutional capacities across regions, impacting energy policies and SPV adoption. The average RUPOP is relatively stable ($SD = 2.61$). The range (12.22 to 20.63) reflects differences in rural demographics, influencing energy demand and infrastructure priorities.

Panel Unit Root Test

To assess data stability over time, we used statistical tests such as the Levin-Lin-Chu, Im-Pesaran-Shin, Fisher’s ADF, and PP tests. These assessments presuppose a certain level of uniformity across the eight South Asian countries studied. Table 4 displays the variables with heterogeneous orders of integration: some are stationary in levels ($I(0)$), while others are integrated in first differences ($I(1)$). Importantly, none of the variables show integration at the second level ($I(2)$).

Table 4.

<i>Stationarity Checking</i>								
	LLCC	IIPS	ADF-Fisher	PP-Fisher	LLCC	IPSS	AUDF	PP-Fisher
	level				1 st Difference			
SPV	-2.93*	-2.68***	-3.99*	-4.28	-9.78***	-9.4708***	-16.20***	-17.32***
RUELEC	-5.82*	0.1416	1.31*	1.24	-12.56***	-14.75***	-20.48***	-21.25***
RUPOP	-1.19	-10.71***	32.01*	-15.58	-5.44***	-2.00**	-2.84***	-3.64***
GDPPC	-0.71	2.3097	2.03	1.9762	-8.06***	-6.75***	-13.48***	-13.58***
GOVTEFF	-2.47**	-2.533***	-3.27*	-3.82*	-27.98***	-8.13***	-12.87***	-13.34***
INST	-2.55*	-1.31*	1.43*	1.51	-5.74***	-4.87***	178***	1.98***

Note. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

Panel Cointegration Test

The study used statistical tests developed by Pedroni, Kao, and Westerlund to determine if there is a long-term relationship between the variables. The results are summarized in Table 5. The analysis showed that there is indeed a long-term

relationship between the variables in most models. While there was some variation across tests, the overall conclusion is that the variables move together in the long run.

Table 5.

<i>Panel Cointegration Test Results</i>	
Variables	Value of statistics
Modified Phillips–Perron t	2.02***
Phillips–Perron t	-2.41***
Augmented Dickey–Fuller t	-2.23***
Kao cointegration test	
Variables	
Modified Dickey–Fuller t	-3.30***
Dickey–Fuller t	-3.50***
Augmented Dickey–Fuller t	-0.9634
Unadjusted modified Dickey–Fuller t	-3.48***
Unadjusted Dickey–Fuller t	-3.55***
Westerlund cointegration test	
Variables	
Variance ratio	-1.44**

Note. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

Baseline Results

Table 6 presents the findings of an LSDV analysis investigating the association between rural electrification and off-grid solar power. The logarithmic transformation of the regressors increases the elasticity of the model coefficients. Periodic patterns are included to account for changes that affect all countries over time, whereas fixed effects capture each country's distinct, time-invariant traits. This approach enables a comprehensive understanding of how rural electrification influences off-grid SPV adoption across nations, accounting for both temporal and country-specific factors.

Table 6.

*The Effect of SPV on Power Accessibility in Rural South Asia,
as Determined by the LSDV Regression Model*

	(1)	(2)	(3)	(4)
	RUELEC _{it+1}	RUELEC _{it+1}	RUELEC _{it+1}	RUELEC _{it+1}
SPV	0.00367 (0.0508)	0.06391*** (0.0114)	0.0615*** (0.0168)	0.0139 (0.0152)
RUPOP	0.874*** (0.0793)	0.950*** (0.0173)	-0.517 (0.524)	-2.319*** (0.562)
GDPPC	0.0723 (0.301)	0.288*** (0.0637)	0.659*** (0.134)	-0.702*** (0.225)
GOVTEFF	0.109 (0.279)	-0.233 (0.144)	-0.483*** (0.157)	-0.276* (0.149)
INST		0.0105 (0.00671)	0.0153* (0.00910)	0.00358 (0.0117)
constant	5.726 (3.670)	1.916** (0.880)	23.94** (9.147)	63.97*** (10.59)
Country-specific effect	Not considered	Not considered	Considered	Considered
Year-specific effect	Not considered	Not considered	Not considered	Considered
N	135	120	120	120
R ²	0.784	0.991	0.995	0.997

Note. Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

This analysis provides outcomes with and without control variables. SPV had a positive and significant influence on RUELEC accessibility ($\lambda_1 = 0.0615$) when controlling for covariates (column 3, Table 6), and this effect remained positive after controlling for country-specific characteristics. However, after accounting for country-specific and year-fixed effects, the correlation became statistically insignificant (column 4). This insignificance may be due to unaccounted-for time-varying shocks across different periods in South Asia, such as extended rainy seasons, catastrophic events, or gloomy weather, all of which might affect solar electricity performance (Rao et al., 2016).

The findings of this study are consistent with previous studies that highlight the potential of the SPV approach for RUELEC in South and Southeast Asia (Almajali et al., 2024; Era, 2024; Imran et al., 2024; Sun et al., 2020). SPV has been widely adopted and supported by government programs such as the National Rural Electrification

Plan (Dellosa & Barocca, 2021). These systems offer a reliable and environmentally friendly energy source, particularly in regions with abundant sunlight (Li & Sahagun, 2023). Compared to diesel-powered generators, SPV systems are more affordable for at least 36 % of unelectrified populations in East Asia, South Asia, and sub-Saharan Africa (Szabó et al., 2021). In Pakistan, a case study identified potential rural sites for solar projects, with Barkhan district in Balochistan emerging as the most suitable location (Iram et al., 2020). Despite challenges such as high upfront costs, solar energy systems provide electricity at a lower cost than conventional sources in these regions, offering a promising solution to energy insecurity and poverty reduction (Iram et al., 2020; Szabó et al., 2021).

According to Jacobson (2007), SPV primarily serves the rural middle class, and improved electricity availability could eventually lead to higher consumption and structural upheaval. The findings in column 4 highlight the need to account for period-based heterogeneities, which may be influenced by missing data.

Incorporating country-specific factors into the analysis reveals that a 10-percentage-point increase in solar power installations can lead to a 0.64-percentage-point increase in rural energy accessibility in the year after the current year. This highlights the positive impact of SPV growth on improving electricity access in rural areas. This finding supports previous research that highlights the cost-effectiveness and environmental benefits of SPV for rural electrification (Irfan et al., 2019). Solar power is especially useful in remote areas where extending traditional electricity grids is difficult or expensive. Electricity can be accessed in these areas through solar power, improving their economic and social development (Uyan, 2013).

The adoption of SPV technology is revolutionizing agriculture and improving living standards for rural populations, especially tiny peasants (Merrouni et al., 2018; Saha, 2025; Saha & Saha, 2023). Bhandari and Stadler (2011) highlight the efficiency of SPV installations in illuminating rural Nepal, where challenging terrain and sparse populations make conventional grid expansion impractical.

Similarly, recent studies demonstrate the economic feasibility of SPV systems in Pakistan and Nigeria. In Pakistan's Balochistan province, SPV electricity costs Rs. 7.98/kWh, significantly cheaper than conventional electricity at Rs. 20.79/kWh (Shah et al., 2018). Similar cost-effectiveness is observed in the provinces of Punjab (Rs. 7.15/kWh) and Sindh (Rs. 6.87/kWh) (Irfan et al., 2019; Xu et al., 2019). These systems also offer substantial environmental benefits, with potential annual CO₂ reductions of 126,000 metric tons in Balochistan and 617,020 metric tons in

Punjab if fully adopted (Irfan et al., 2019; Shah et al., 2018). In Nigeria, a proposed PV electrification model for the Federal Capital Territory demonstrates economic viability, with a financial internal rate of return of 17.5 % and a net present value of N320,897,841 (Izuchukwu & Peace, 2021). These findings suggest that SPV systems are not only more affordable than traditional energy sources but also help reduce carbon emissions in both countries.

Centralized SPV systems have proven effective in providing reliable electricity to rural households, as noted by Doan et al. (2023) and Fahmi et al. (2014). This highlights the potential of renewable energy to address the energy needs of farming communities while fostering sustainability. SPV systems reduce reliance on expensive, environmentally harmful fossil fuels, providing a steady energy supply that supports irrigation, cold storage, and other agricultural activities crucial to productivity.

Beyond agriculture, SPV enhances the overall quality of life by powering essential services such as lighting, healthcare, and education. Its affordability and adaptability make it a practical solution for rural electrification, bridging the energy gap in underdeveloped regions. As renewable energy technologies advance, SPV emerges as a sustainable pathway to rural development, empowering communities, reducing poverty, and contributing to global environmental goals. This transformative potential underscores the importance of integrating SPV into rural development strategies worldwide.

The RUPOP ratio has a significant impact on rural energy availability (λ_2), but not always positively. This is consistent with Balachandra (2011) and Han and Wu (2018), who emphasize the economic hurdles of expanding electrical networks and energy infrastructure into sparsely populated rural areas. The higher per capita costs in such areas reduce the appeal of utilities and governments, often limiting investment.

Even with control factors (column 3) and country-specific fixed effects, GDP per capita (GDPPC) remains positively correlated with rural energy availability ($\lambda_3 = 0.659$). However, in column 4, the inclusion of year-specific effects reveals an unexpectedly negative trend. This shift could indicate scenarios in which economic growth is not inclusive, disproportionately benefits urban areas, or fails to distribute gains evenly between rural and urban inhabitants.

An intriguing finding is the inverse impact of government effectiveness (GOVTEFF) ($\lambda_4 = -0.276$) on RUELEC accessibility in the following year. This

unexpected outcome may stem from efficient governments prioritizing urban areas because of their economic and revenue-generating advantages, often neglecting rural electrification programs. Additionally, strict regulations implemented by effective governments to ensure compliance with environmental and public safety standards can increase the expenses and complications of rural energy systems, discouraging investment (Cook, 2011). Corrupt practices further compound the issue, as officials may demand bribes for project approvals, leading to inflated costs, interruptions, and substandard structures (Debnath & Mourshed, 2018).

The findings in columns 1–4 indicate that off-grid clean energy sources may be an attractive alternative to traditional grid-based energy, particularly in areas where government policies and practices hamper rural electrification. These findings suggest that off-grid solutions may play a crucial role in increasing energy availability in underserved areas, bypassing existing infrastructure and governmental constraints.

By leveraging decentralized energy solutions like SPV and other renewables, rural communities can bypass the challenges associated with centralized grid expansion. Off-grid systems not only reduce reliance on inefficient governance but also offer cost-effective, sustainable energy solutions tailored to the needs of underserved areas. These insights highlight the critical role of renewable energy in bridging the rural-urban energy divide while addressing governance-related barriers.

Lewbel 2SLS Findings

Table 7 shows the results of the Lewbel 2SLS strategy, as described in the estimation process. This method provides more insight into the association of SPV installations and remote electricity accessibility (RUELEC), demonstrating a much stronger and more adaptive association than LSDV estimates. The Lewbel IV technique emphasizes the catalytic effect of SPV in advancing rural electrification, especially when standard research may underestimate its influence. By addressing endogeneity issues, the Lewbel technique provides a more accurate assessment of SPV systems' potential to improve rural energy access.

This broader vision has significant consequences for policy and development. SPV systems serve as both a power source and a catalyst for rural transformation. SPV systems promote local economic growth, improve education, and advance healthcare by increasing access to power. The Lewbel IV approach emphasizes their role in promoting sustainable energy solutions, laying the road for long-term growth. These systems empower rural communities by bridging

Table 7.

<i>Results of the IV and 3SLS</i>		
	Lewbel IV	3SLS
	RUELEC_{it+1}	RUELEC_{it+1}
INST	-0.0624 (0.0475)	0.0139* (0.00822)
SPV	0.120*** (0.0230)	0.0512*** (0.0154)
RUPOP	-1.614* (0.877)	-0.246 (0.479)
GDPPC	0.178 (0.124)	0.711*** (0.125)
GOVTEFF	0.344 (0.421)	-0.512*** (0.145)
Country fixed effect		Considered
N	120	119
R ²	0.322	0.995

Note. Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

energy gaps and offering chances for social and economic improvement, making them an essential component of long-term rural development initiatives.

The Lewbel IV approach weakens the effects of income intensity (GDPPC) and government restrictions (GOVTEFF) on electrification in the region, emphasizing the independent value of SPVs. This implies that SPVs can be a valuable instrument for supporting equitable development, particularly in resource-constrained or politically insecure areas. SPVs provide a practical alternative for empowering local populations, assuring sustainable progress, and improving energy access in underserved areas, all of which contribute to long-term development goals in these regions.

The Lewbel IV method emphasizes SPV's revolutionary potential, indicating that it has a greater impact on rural electrification regardless of external conditions. This study provides convincing support for prioritizing SPV investments in rural development plans. We can use solar power to light homes and entire towns, promoting a sustainable future for people and the environment.

3SLS Analysis

The 3SLS approach is a powerful econometric tool that addresses common technical issues, including endogeneity and contemporaneous residual correlation, that are prevalent in single-equation and multivariate Granger causality models. [Table 7](#) displays the 3SLS estimates, which highlight its ability to estimate a collection of equations by simultaneously estimating all model parameters. This strategy provides for possible associations in disturbance terms within the framework and effectively reduces endogeneity by employing instruments such as lagged variables. Compared to the 2SLS approach, 3SLS is more reliable and robust, yielding more precise parameter estimates in complex settings ([Arellano & Bover, 1990](#)). By overcoming the limitations of simpler methodologies, 3SLS delivers more accurate analysis in situations with numerous interconnected equations, yielding more reliable econometric modeling outcomes.

Simultaneous equation estimation in 3SLS provides a thorough understanding of the model's interdependencies, making it ideal for investigating systems with multiple endogenous variables. Furthermore, by resolving the constraints of 2SLS, 3SLS minimizes bias in parameter estimation, thereby increasing precision in econometric modeling. These features make 3SLS an indispensable tool in empirical research, particularly when investigating relationships driven by feedback loops or shared shocks between equations. [Table 7](#) shows that 3SLS provides excellent insights into structural dynamics, underscoring its usefulness in advanced econometric analysis.

Sensitivity Analysis

We assess the robustness of our findings using two approaches:

- **Sub-Period Analysis:** We calculate the variables' three-year averages while maintaining the model specification and estimation methodologies constant.
- **Alternative Estimation Methods:** To ensure robust estimation and address specific data features, such as heteroskedasticity, autocorrelation, and cross-sectional dependence, panel data analysis uses methods such as PCSE and FGLS.

The first sensitivity test, which used three-year sub-periods, found that the coefficient direction remained constant ([Table 8](#)). Key findings include:

- **Increased Coefficient Magnitudes:** The coefficients for independent variables in each model are significantly larger, indicating stronger links

between SPV and rural electrification when studied over shorter time periods. This shows that SPV adoption has a more immediate and significant influence on rural energy access.

- **Control Variable Stability:** Control variable coefficients are typically consistent with baseline results, except for a few exceptions, such as income intensity and governmental regulations.
- **Higher R-squared values:** The R-squared values are higher than those in the baseline results (Table 6), implying that studying SPV's impact on rural energy over shorter time periods may reveal further intricacies.

Table 8.

Estimation Results Regarding the Influence of the Solar Power System on Energy Accessibility, Averaging a Three-Year Period

	(1)	(2)	(3)	(4)
	RUELEC _{it+1}	RUELEC _{it+1}	RUELEC _{it+1}	RUELEC _{it+1}
SPV	0.00678 (0.0581)	0.0861*** (0.0191)	0.0960*** (0.0307)	0.0124 (0.0264)
RUPOP	0.842*** (0.0945)	0.931*** (0.0295)	-1.181 (0.941)	-3.299*** (0.868)
GDPPC	0.142 (0.379)	0.278** (0.115)	0.492* (0.249)	-0.851*** (0.305)
GOVTEFF	-0.0393 (0.370)	-0.143 (0.292)	-0.662* (0.330)	-0.377 (0.263)
INST		0.00394 (0.0131)	0.0123 (0.0201)	-0.00818 (0.0218)
Constant	5.545 (4.562)	2.608 (1.585)	36.39** (16.54)	82.17*** (16.18)
Country-specific effect	NO	NO	YES	YES
Year-specific effect	NO	NO	NO	YES
N	54	46	46	46
R ²	0.845	0.989	0.994	0.998

Note. Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

Given these findings, it would have been ideal to assess sensitivity over extended sub-periods, such as 8-year periods, to capture longer-term trends. However, this strategy is not viable due to limitations in sample size and data availability.

To obtain reliable results, we employed PCSE to address concerns such as measurement error and data-point correlation. We also employed FGLS to ensure the credibility of our findings. FGLS accounts for the variance structure by using a weighted least-squares estimator to improve parameter estimates when the data are weak or inefficient. FGLS, unlike fixed-effects models, retains time-invariant variables by adjusting the cluster means using a factor (θ , theta) between 0 and 1 to improve statistical precision (Koreisha & Fang, 2001).

Omitting country- and period-fixed effects reduced the explanatory power, underscoring the need to account for heterogeneity across nations and time periods in panel data analysis. The results from the PCSE and FGLS approaches (reported in Table 9) are quite similar to the baseline findings, with the explanatory factors showing consistent direction, significance, and explanatory power.

Table 9.

<i>PCSE and FGS Estimation Results</i>		
	PCSE	FGLS
	RUELEC_{it+1}	RUELEC_{it+1}
SPV	0.0139 (0.0156)	0.0349*** (0.12)
GDPPC	-0.702* (0.376)	-0.717*** (0.18)
RUPOP	-2.318*** (0.411)	-2.743*** (0.349)
GOVTEFF	-0.275** (0.127)	-0.140 (0.0897)
INST	0.00357 (0.00911)	
Constant	63.98*** (8.894)	73.95*** (6.865)
Country-specific effect	YES	YES
Time-specific effect	YES	YES
N	120	128
R ²	0.997	0.999

Note. Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: Own elaboration

This dual-method approach enhances the trustworthiness of the research by ensuring that the conclusions are robust to various econometric challenges. The combination of PCSE and FGLS provides a comprehensive framework for handling panel-data complexity and yields insights that are consistent across different estimation methodologies.

CONCLUSIONS AND POLICY IMPLICATIONS

Access to electricity is a key issue in South Asian countries, where poverty persists, particularly in remote areas, and efforts to achieve the SDGs are sometimes hampered. Location with scarce grid-based energy restricts agricultural output, stifles structural reform, and impedes poverty-reduction efforts. In this context, the SPV approach stands out as a prospective decentralized energy alternative. They offer an affordable, environmentally friendly alternative to conventional energy sources, especially in rural areas where grid connectivity is either unavailable or prohibitively expensive to provide.

Although there has been increased interest in renewable energy sources, the relationship between energy accessibility in remote areas and off-grid technologies, such as SPV, remains poorly understood. The influence of off-grid SPVs on enhancing energy availability in rural regions, particularly their role in promoting economic and social development, remains understudied. This research aims to fill that knowledge gap by investigating the potential of SPV systems to expand power access and livelihoods, and to contribute to achieving broader development goals in rural South Asia. The study's focus on off-grid technology aims to shed light on how solar energy might support sustainable development in underprivileged areas.

This study uses a variety of econometric techniques, including LSDV, Lewbel IV, and 3SLS, to evaluate the role of off-grid SPV systems in improving accessibility to RUELEC, as measured by power accessibility rates. The findings show that SPV adoption has a considerable positive influence on alleviating energy shortages and promoting rural development. The study's robustness tests underscore the need to account for country-fixed constraints that determine the association between SPV adoption and power access. These considerations include local economic conditions, policy frameworks, and infrastructure constraints, which may differ greatly across places. Recognizing these dynamics is critical for performing detailed analysis and devising specific solutions to improve rural electrification efforts. The study highlights

the effectiveness of solar infrastructure, emphasizing its potential to increase sustainable energy access in neglected rural areas. Furthermore, understanding the underlying factors driving this relationship is critical for policymakers and development organizations seeking to build more targeted, effective initiatives that improve energy access while also advancing broader socioeconomic development goals.

The findings offer critical, evidence-driven insights for policymakers and development practitioners. To address seasonal weather variability that can undermine SPV performance, governments should pair PV systems with short-term battery storage or hybrid solutions (solar-wind or solar-diesel), directing subsidies specifically toward storage components rather than panels alone. Rather than relying solely on central-government-led rural electrification, which often prioritizes urban areas, South Asian countries should establish independent rural energy agencies with delegated authority, replicating successful models such as Bangladesh's Infrastructure Development Company Limited (IDCOL). Policy measures should also include progressive energy tariffs or targeted subsidies for the bottom income quintile, leveraging digital payment platforms (e.g., India's UPI, Bangladesh's bKash) to deliver direct cash transfers for SPV adoption, thereby ensuring that economic growth translates into tangible energy access for the poor. In politically unstable or remote regions such as Pakistan's Balochistan and Afghanistan's rural provinces, creating off-grid SPV corridors through public-private partnerships with output-based aid is recommended. This approach requires minimal government intervention, focusing instead on reducing import tariffs on PV components and facilitating microfinance through local NGOs. Finally, in sparsely populated areas, promoting community mini-grids rather than individual home systems lowers per-household costs, and governments should offer capital subsidies that cover a significant share of mini-grid setup costs, recoverable through pay-as-you-go metering.

Despite the optimistic findings, the study has certain limitations, particularly due to data shortages in some South Asian nations. These constraints highlight the need for future research to use advanced econometric methodologies, such as the Generalized Method of Moments (GMM), to address potential endogeneity. Furthermore, more research is needed to determine how SPV systems might maximize the benefits of non-agricultural rural transformation, such as improved rural industries and services. Researchers should also investigate how SPV adoption affects farmers' productivity and efficiency, the duration of adoption, and detectable effects on agriculture and rural development. By addressing these concerns, future research can provide deeper insight into the long-term effects of SPV on

rural economies and contribute to more effective policy development to encourage sustainable rural growth.

Addressing these research gaps is critical for developing a more robust evidence foundation to guide policy and program design. A better understanding of these factors may help policymakers develop more effective interventions to promote the uptake and integration of SPV systems into rural development frameworks. Extending SPV's role in South Asia's energy strategy has the potential to transform rural energy access, catalyze economic growth and social progress, and pave the way for a more sustainable and equitable future.

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The authors declare no conflict of interest.

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The raw data that support the findings of this study are available upon request from the corresponding author.

AUTHORS' CONTRIBUTIONS

RA: Conceptualization, data curation; SBH: Literature review, data preparation; SKS: Conceptualization, methodology, data preparation, data curation, coding of the statistical software, visualization, formal analysis, investigation, writing, supervision, statistical program, coding of the statistical software, literature reviews. The authors have read and agreed to the published version of the manuscript.

AI USAGE STATEMENT

In preparing this manuscript, AI tools, specifically ChatGPT (GPT-5-mini), were used to assist with literature searches, summarization, and formatting guidance. All ideas, analyses, interpretations, and conclusions presented in this work are solely those of the authors. The AI tool did not generate original content, perform data analysis, or influence the substantive academic arguments of the manuscript.

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