Policies, Infrastructure, and Technology in Advancing Off-Grid Solar Energy Systems in the Global South

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ABSTRACT
In the Global South, access to reliable electricity remains a significant barrier to socioeconomic development, with traditional grid-connected solutions often unable to reach remote areas due to prohibitive costs and logistical challenges. This study examines the potential of off-grid solar energy systems as a viable alternative, using a systematic literature review to evaluate the influence of policies, infrastructure, and technological integration with national grids. The analysis highlights the role of advanced technologies—such as data analytics, monitoring systems, and smart grids—in improving the efficiency and sustainability of these systems. Preliminary findings underscore the importance of an integrated approach, combining policy support, technological innovation, and robust infrastructure to maximize the impact of off-grid solar energy. This research contributes to global energy equity efforts and aligns with Sustainable Development Goal 7, which seeks to ensure universal access to affordable, reliable, and sustainable energy.

INTRODUCTION

Reliable electricity is a cornerstone of socioeconomic development, directly impacting quality of life, economic productivity, education, and health outcomes. However, in the Global South, many regions lack access to dependable electricity, creating a critical barrier to poverty alleviation and long-term development. Conventional energy solutions, such as grid-based systems powered by fossil fuels, often fail to reach remote and underserved communities due to high costs and logistical challenges. Thus, off-grid solar energy has emerged as a promising alternative, offering scalable, sustainable, and cost-effective solutions.

Still, the widespread adoption and long-term sustainability of off-grid solar systems face significant challenges. High upfront costs, inadequate maintenance frameworks, fragmented policy support, and limited integration with national grids limit the ability of these systems to deliver lasting effects. Also, while off-grid solar projects have shown significant short-term gains, their role in driving long-term sustainable development remains underexplored [8].

This work seeks to address these gaps by examining how policies, infrastructure, and technological innovations influence the success of off-grid solar energy initiatives in the Global South. Specifically, our research question is: for communities in the Global South lacking reliable electricity, how do policies, infrastructure, and technological integration of off-grid solar energy with national grids impact long-term socioeconomic development compared to traditional energy sources?

We investigated the integration of off-grid solar with national grids and advanced technologies like data analytics, monitoring systems, and smart grids through a systematic literature review. This review examines how these technologies enhance the accessibility and sustainability of off-grid solar systems, comparing their socioeconomic impacts to traditional energy resources while identifying the enabling conditions for long-term success. Using the PICO framework, we systematically categorized and analyzed findings across diverse geopolitical and socio-economic contexts to develop strategies for effective off-grid solar deployment.

The study provides actionable insights for policymakers, practitioners, and stakeholders seeking to leverage off-grid solar for sustainable development. Preliminary evidence highlights the importance of an integrated approach—combining policy support, advanced technologies, and robust infrastructure—to maximize the impact on underserved communities. Successful implementation not only improves energy access but also fosters economic empowerment through local employment and innovative business models like pay-as-you-go systems. Smart grid integration enhances distribution reliability and efficiency, reducing energy wastage and operational costs. By aligning our findings with Sustainable Development Goal 7, we underscore the transformative potential of off-grid solar systems in achieving equitable and sustainable energy access globally.

RELATED WORK

The growing interest in renewable energy solutions for underserved communities has led to significant research of off-grid solar energy systems. Prior work has extensively explored the socioeconomic impacts, technological advancements, and policy frameworks necessary to scale these solutions. However, challenges such as sustainability, long-term affordability, and integration with national grids remain inadequately addressed. This section thematically organizes prior work, identifying gaps and highlighting how this study seeks to address them.

Socioeconomic Impacts of Off-Grid Solar Energy

Off-grid solar energy systems, such as Solar Home Systems (SHS) and mini-grids, have significantly advanced socioeconomic development in rural and underserved areas. By replacing kerosene lamps with clean and reliable electricity, these systems reduce household expenses, improve health outcomes, extend working hours, and decrease pollution [2, 8, 9], leading to measurable increases in productivity and income levels.

Despite these benefits, the broader ripple effects on local economies remain underexplored. Solar-powered micro-enterprises, often vital to rural economic ecosystems, are constrained by limited access to capital and market linkages [2]. Programs like micro-loans for solar-powered equipment show promise in bridging these gaps. For example, solar cooperatives in Uganda have demonstrated success, boosting agricultural productivity through shared solar irrigation systems [1]. Linking off-grid solar projects with vocational training in areas like sustainable agriculture could further enhance resilience by enabling communities to leverage energy access for long-term development. A multidimensional approach that combines clean energy with targeted capacity-building programs could unlock synergies between socioeconomic development and energy equity.

Sarker et al. (2020) [9] quantified the economic returns of SHS in Bangladesh, showing that households using SHS units of 30 Wp or higher achieved high economic returns, with a positive net present value (NPV) and internal rate of return (IRR) for income-generating activities. Each unit also prevents up to 7.34 tons of $CO2$ emissions over 20 years, highlighting environmental benefits of transitioning away from kerosene lamps.

While these studies highlight immediate benefits, they often overlook long-term impacts, such as income stability, intergenerational education improvements, and broader economic growth. This research addresses these gaps by examining structural factors—policies, infrastructure, and technological innovation—that underpin the sustained economic viability of off-grid solar systems, offering actionable insights for achieving long-term socioeconomic development.

Challenges in Sustainability and Maintenance

A persistent challenge in off-grid solar energy systems is ensuring their long-term sustainability and maintenance. While these systems offer immediate benefits, several critical barriers hinder their long-term adoption and effectiveness:

Fragmented Technological Implementation. Radley and Legmann-Grube (2022) [8] critique the fragmented approach to deploying technologies like pay-as-you-go (PAYG) models. While these models increase market reach and make off-grid solar accessible to low-income households, they often fail to integrate with broader policy frameworks. This misalignment reduces the potential for long-term socioeconomic benefits, as the systems lack the necessary infrastructure and support for scalability. The authors advocate for incorporating data analytics and smart grid systems to optimize infrastructure gaps, improve decision-making, and integrate off-grid systems with national energy grids. For instance, smart grids can facilitate predictive maintenance and improve reliability in remote areas, where logistical challenges are more pronounced. This study builds on these findings by investigating how integrated technological solutions can address infrastructure gaps and enhance the long-term functionality of off-grid systems.

Affordability and Upfront Costs. High upfront costs remain a significant barrier to SHS adoption, especially in rural communities. Sarker et al. (2020) [9] found that systems capable of income-generating activities, such as 30 Wp or higher, cost between $400 and $600 USD in Bangladesh – an investment beyond the reach of many rural households where median monthly income often falls below $100. Additionally, battery replacement every 3-5 years adds to lifecycle costs, further burdening low-income users. Even with PAYG models that allow for incremental payments, the total cost over time often remains unaffordable without financial assistance. This affordability gap is then compounded by the lack of widespread microfinance options or government subsidies to reduce costs.

Hellqvist and Heubaum (2022) [4] also provide a detailed case study of the Bangladesh SHS program, which initially succeeded in addressing affordability through microcredit schemes, public-private partnerships (PPP), and donor-funded subsidies. These financial mechanisms made SHS accessible to rural households, but the program's reliance on subsidies became a critical weakness. As subsidies declined and the government shifted focus to promoting grid expansion and offering free solar systems, demand for SHS dropped sharply. This highlights the limitations of donor-dependent models, emphasizing that to overcome affordability challenges, governments and stakeholders must design financial support systems that are scalable and not overly reliant on temporary subsidies. Innovative, long-term, and scalable financing models such as revolving loan funds, tax incentives, and hybrid funding models that combine public and private investment could provide solutions.

Maintenance Gaps and Environmental Risks. Maintenance is another critical issue undermining the sustainability of off-grid solar systems. Energy firms frequently place the responsibility of system repairs on end-users and communities [8], who often lack the technical skills or resources to address malfunctions. This approach leads to inconsistent functionality and decreases user trust in solar technologies, which is then exacerbated by weak regulatory oversight on end-of-life management for solar components [4].

Battery disposal is another pressing environmental challenge, as batteries have to be replaced every 3-5 years (usually closer to 3) [1], yet rural areas often lack access to safe disposal facilities [9]. Improper disposal practices not only harm the environment but also reduce the sustainability of off-grid systems. Successful models in countries like Rwanda, where public and private partnerships incentivize battery recycling through tax rebates, highlight a viable pathway to address this issue [3]. Governments could further address this by introducing subsidies for eco-friendly technologies or establishing regional recycling hubs to leverage economies of scale and reduce operational costs.

IoT-based monitoring systems offer promising solutions to maintenance challenges by offering real-time data collection and predictive maintenance [6]. These systems can reduce downtime and extend the operational lifespan of systems, but high costs and limited connectivity remain significant barriers to widespread adoption [8]. Pilot projects in Kenya demonstrate the effectiveness of integrating IoT solutions with community training programs, empowering local technicians and fostering a sense of user ownership [5]. This study expands on these findings by exploring scalable IoT-based maintenance solutions and advocating for cohesive regulatory measures to improve quality control and battery disposal practices.

These challenges highlight the need for a more integrated approach to sustainability and maintenance. By addressing affordability, technical gaps, and regulatory weaknesses, this study seeks to provide practical recommendations for improving the longevity and scalability of off-grid solar energy systems.

Policy and Regulatory Frameworks

Policy and regulatory frameworks play a pivotal role in shaping the success and scalability of off-grid solar energy systems, particularly in regions where traditional grid infrastructure remains inaccessible and unreliable. These frameworks influence the legal, financial, and operational environments necessary for fostering sustainable energy solutions.

Enabling Private Sector Participation. The participation of private entities is essential for scaling off-grid energy solutions, but this requires conducive regulatory frameworks. The International Renewable Energy Agency (IRENA) highlights that clear legal provisions are critical for enabling private sector actors to generate, distribute, and sell electricity through mini-grids and solar home systems (SHS) [5]. Streamlined licensing processes, e.g., single-window clearance facilities implemented in Tanzania, reduce administrative barriers and attract private investment. Furthermore, differentiated tariff structures tailored to rural contexts in regions of Bangladesh and Kenya have proven effective in addressing cost disparities between off-grid solutions and grid-based systems, ensuring affordability while maintaining economic viability for operators.

Challenges in Coordinating Policy Objectives. The Bangladesh Solar Home Systems (SHS) Program [4] demonstrates both the potential and pitfalls of policy-driven off-grid electrification. As Hellqvist and Heubaum (2023) discussed, competing policy priorities such as the introduction of free solar systems and simultaneous expansion of traditional grid infrastructure undermined the program's viability despite an initial success with 4 million units deployed in 2013. A lack of coordination led to off-grid market saturation and financial instability for the program's partners which ultimately led to slower adoption rates.

Strengthening Regulatory Oversight. Effective regulatory oversight in technical and interconnection standards is crucial to ensure the quality and sustainability of off-grid systems. The lack of regulatory enforcement in monitoring the quality of imported solar components in the Bangladesh SHS program [4] led to the proliferation of substandard products which contributed to the decline of consumer trust and consequently limited the long-term success of the program. Additionally, a lack of clear integration guidelines and interconnection standards for integrating mini-grids with national grids upon entry in Tanzania resulted in many operators facing stranded assets and financial losses [5]. To mitigate these challenges, local regulatory frameworks must prioritize the enforcement of technical standards to ensure the quality and reliability of off-grid components, combined with the establishment of clear integration guidelines (when necessary) with existing national infrastructure to protect investments and support long-term sustainability and scalability of off-grid energy solutions.

Integration of Technology with Infrastructure

The integration of technology with infrastructure in off-grid solar systems is pivotal for enhancing their efficiency and scalability. Technologies such as IoT-based monitoring systems, smart grids, and data analytics have emerged as critical tools to help bridge the gap between decentralized energy solutions and national energy systems, creating hybrid models capable of adapting to the needs of underserved communities.

IoT-Based Systems. As previously identified, IoT-based systems provide real-time data collection and monitoring to enable predictive maintenance. López-Vargas et al. (2021) [6] highlight how IoT-enabled Solar Home Systems can proactively identify faults and optimize energy usage by tracking system performance metrics such as battery health, solar panel efficiency, and load consumption.

However, implementing IoT-based systems requires robust infrastructural support, including reliable connectivity and access to technical expertise, which, in many remote areas, is limited.

Smart Grids. Smart grids are essential for integrating off-grid solar systems with national energy infrastructure. The International Renewable Energy Agency (2016) [5] emphasizes their role in real-time load balancing, energy storage management, and optimized energy distribution, enabling hybrid systems that combine decentralized solar with grid power. This approach addresses a major limitation of off-grid systems: their limited scalability without centralized infrastructure. Advancements in energy storage technologies, such as lithium-ion batteries, are critical for scaling hybrid off-grid systems. In Zambia, these systems have reduced energy wastage by 25% and extended the lifespan of critical infrastructure [1]. Additionally, blockchain technology integrated into off-grid networks enables peer-to-peer energy trading, empowering communities to generate income while decentralizing energy distribution and enhancing grid reliability.

Data Analytics. Data analytics is another transformative tool for optimizing off-grid solar system performance and enabling better decision-making. López-Vargas et al. (2021) [6] note that the integration of advanced data analytics with IoT systems allows providers to predict energy demand, monitor payment patterns in PAYG models, and tailor energy solutions to the needs of specific communities.

Data analytics also play a critical role in financial planning – Sarker et al. (2020) [9] emphasize the affordability challenges faced by rural households when adopting SHS systems. By integrating financial data with energy usage metrics, providers can develop adaptive payment plans and financing models that cater to the unique circumstances of low-income, rural users. This ensures both the economic viability of energy providers and the accessibility of off-grid solar systems.

While the potential benefits of integrating technology with infrastructure are substantial, significant challenges remain, from connectivity gaps to cost barriers and policy limitations. This study seeks to address these gaps by proposing alternative hybrid connectivity solutions; analyzing how policy can be modified to better establish energy-sharing standards; and discussing the development of centralized data platforms that aggregate information from various systems.

Gender and Equity Considerations

The integration of off-grid solar technologies has shown transformative impacts on gender and equity and broader social inclusion in energy-deprived regions of the Global South. Specific interventions such as solar mini-grids and decentralized renewable energy systems are addressing systematic barriers faced by marginalized groups (i.e., women and low-income households).

Access to Education and Gender Equality. Solar mini-grids have significantly improved gender equity in education by reducing the reliance on school-aged children (particularly girls), for household chores like water and fuel collection. A cohort study in Kenya and Nigeria [2] showed a 29% decrease in children tasked with fetching water following mini-grid installation which directly correlated with increased school attendance. As compared to using traditional fuel methods before the mini-grid, 53.4% of households reported using children for water collection, dropping to 15% post-installation. Households also spent 15 fewer hours on water collection and 36 fewer hours on fuel collection per 100 households.

Hellqvist (2021) [3] also adds that modern energy access in Kenya alleviates reliance on traditional fuels like wood and dung, which disproportionately consume women’s time and limit their ability to engage in education or business opportunities. By addressing these systematic inequalities, off-grid solar systems not only enable better education outcomes but also foster long-term social mobility for girls and women.

Economic Empowerment of Women. The impact of mini-grids on women's economic opportunities has shown mixed results. Carabajal et al. (2024) [2] observed a drop in women-owned businesses from 28% to 19% post-connection to solar mini-grids, likely due to broader economic pressures. However, 17% of surveyed organizations reported hiring at least one female worker after mini-grid installations, with every 10 additional households connected associated with one new business employing a woman. This suggests potential growth in women’s labor market participation.

Hellqvist (2021) [3] highlights macroeconomic policies' role in empowering women through energy access but notes systemic barriers, such as lack of credit access. For example, women in Kenya hold only 1% of land titles, restricting their ability to secure loans for energy systems. Addressing these issues requires targeted solutions, such as integrating vocational training into off-grid initiatives. Evidence from East Africa shows that training women in solar installation and maintenance boosts economic independence and diversifies the energy workforce [6, 8]. Tailored financing mechanisms, including subsidies for technical appliances combined with solar systems [3], can help women transition into sustainable economic activities and foster inclusivity.

METHODS

1: Planning the Review

To investigate the research question outlined in the Introduction, we conducted a systematic literature review by defining our research protocol to follow the PICO (Population, Intervention, Comparison, Outcome) framework outlined in [7]. The PICO framework is a popular clinical systematic review framework that provides a structured approach to deconstruct the full research question into clear and actionable search concepts to ensure a comprehensive search strategy to allow us to identify relevant and consistent papers throughout the review process.

1.1 Population

1.1.1 Inclusion Criteria

We defined our inclusion criteria for studies to be underserved communities in the Global South lacking reliable electricity solutions with a primary focus on communities that have implemented off-grid electricity solutions.

1.1.2 Exclusion Criteria

We defined our exclusion criteria for studies that were not focused on the Global South, communities that have implemented grid-based electricity solutions. We set the keyword search's timeframe for most papers cited to be within the last decade (2014-2024) to capture the critical period for technological and policy evolution in off-grid energy. Much of this expansion has been driven by foreign direct investment, with global off-grid solar capacity increasing tenfold during this period. [8]

1.2 Intervention

We defined our scope for acceptable studies by outlining two key criteria for the intervention:

1. Studies must focus on the deployment of off-grid energy infrastructure, including but not limited to Solar Home Systems (SHS), mini-grids, and other comparable technologies designed to provide energy access in remote or underserved regions.

2. Studies should incorporate the use of advanced computational methods or technologies to enhance the efficiency, monitoring, or adaptability of energy solutions. This includes, but is not limited to, artificial intelligence methods for data analytics, monitoring systems, smart grid technologies, Internet of Things (IoT) sensors, hybrid energy systems, and other innovations that leverage computational capabilities.

1.3 Comparison

We defined our comparison criteria for eligible studies to either include a clear mention of traditional energy resources (e.g., fossil fuels such as coal, oil, and natural gas) or grid-based systems as a baseline for evaluation. This allowed us to assess the relative performance, scalability, and sustainability of off-grid renewable energy solutions against established energy frameworks.

Studies were required to provide either a direct comparison of outcomes, such as energy access, cost efficiency, or environmental impact, or contextual information highlighting the physical or technological limitations of traditional energy sources in specific settings.

1.4 Outcome

To assess the long-term socioeconomic impacts of off-grid solar energy in the Global South, we established the following seven key outcome criteria for the included literature:

1. **Poverty Reduction:** Measured through changes in employment opportunities, poverty rates, and access to financial services like microfinance.
2. **Technological implementation:** Measured by the effective utilization of advanced technological tools outlined in Section 1.2.
3. **Infrastructure Integration:** Assessed through the ability of off-grid systems to integrate with national grids, improving energy reliability, scalability, and accessibility for underserved communities.
4. **Policy Effectiveness:** Evaluated based on the presence and impact of supportive regulatory frameworks, subsidies, public-private partnerships, and alignment with SDG 7.
5. **Education:** Evaluated by improvements in school enrollment and completion rates, along with enhanced educational infrastructure enabled by reliable energy access.
6. **Economic Productivity:** Assessed using metrics such as internal rate of return (IRR), net present value (NPV), and the growth of local businesses.
7. **Quality of Life:** Tracked through indicators like access to electricity, time savings, and environmental benefits such as carbon emission reductions.

2: Search Criterion

2.1 Framework Keywords

We operationalized our search strategy by defining keywords for each PICO framework concept:

Population: Global South; developing countries; energy-deprived regions; underserved communities; rural electrification; energy poverty; countries with unreliable electricity access (e.g., Bangladesh, Sub-Saharan Africa)

Intervention: Off-grid solar energy; Solar Home Systems (SHS); mini-grids; renewable energy infrastructure; solar-battery hybrid systems; smart grids; data analytics; IoT systems

Comparison: Traditional energy resources (e.g., fossil fuels, coal, oil, gas); diesel generators; grid-based electricity; conventional energy systems

Outcome: Socioeconomic impact; poverty reduction; employment; economic development metrics (IRR, NPV); health improvement; carbon emission reductions; sustainability and resilience

2.2 Search Strategy

2.2.1 Feasibility

To ensure a comprehensive and focused systematic literature review, we used the keywords defined for each PICO framework concept in Section 2.1 to construct our search strategy. The keywords were helpful in identifying relevant literature addressing the intersections of off-grid solar energy, technological integration, policy frameworks, and socioeconomic development in the Global South.

2.2.2 Methodology

We conducted our search across Google Scholar and Web of Science's academic databases. Our search methodology utilized Boolean operators (AND, OR, NOT) to construct search queries which allowed us to refine results by controlling which terms must, may, or must not appear in our literature reviewed.

2.2.3 Example Search String

Input Query	*("Global South" OR "Bangladesh") AND ("off-grid solar energy" OR "Solar Home Systems" OR "SHS")*
Output (Top 3 Results Returned)	"Setting the Sun on Off-Grid Solar?: Policy Lessons from the Bangladesh Solar Home Systems (SHS) Programme" "Surge in Solar-Powered Homes: Experience in Off-Grid Rural Bangladesh" "Off-Grid Solar Expansion and Economic Development in the Global South: A Critical Review and Research Agenda"

Using the PICO framework, we systematically identified relevant literature, enabling a comprehensive review of the key factors and challenges to the success of off-grid solar energy initiatives in underserved regions of the Global South.

FINDINGS

This study provides key insights into how policies, infrastructure, and technological innovations influence the success of off-grid solar energy systems in the Global South. By systematically reviewing existing literature, we identified critical findings that address our research question: *How do policies, infrastructure, and technological integration of off-grid solar energy with national grids impact long-term socioeconomic development compared to traditional energy sources?*

Socioeconomic Impacts

Off-grid solar energy systems have demonstrated significant short-term benefits, particularly in improving quality of life, economic productivity, and environmental sustainability. For instance, Sarker et al. (2020) [9] report that SHS units of 30 Wp or higher generate high economic returns, with positive net present value (NPV) and internal rates of return (IRR) for small enterprises. Carabajal et al. (2024) [2] illustrate how solar mini-grids in Kenya and Nigeria quadrupled household incomes by enabling small businesses to adopt modern equipment and extend working hours. Additionally, access to clean energy facilitates better educational outcomes by providing consistent lighting for studying and improving school attendance rates in rural areas. The environmental benefits of SHS systems are also notable, with each unit offsetting up to 7.34 tons of CO_2 emissions over its 20-year lifecycle [9].

Beyond individual household benefits, the cumulative impact of off-grid solar systems on regional development are monumental. For instance, solar mini-grids in Sub-Saharan Africa have spurred local industrial activities, enabling the establishment of rural manufacturing units and processing facilities, improving good security and household incomes [1]. Moreover, these systems create new job opportunities, ranging from installation technicians to system maintenance experts, with studies estimating that every 100 SHS installations generate at least five full-time equivalent jobs in rural economies. These broader impacts emphasize the transformative potential of scaling off-grid solar energy to catalyze holistic socioeconomic development.

However, these short-term gains do not fully capture the long-term socioeconomic impacts of off-grid solar systems. To address this, we propose linking solar systems to broader community resources, such as education-focused initiatives and community energy hubs, to sustain and amplify their impact over time. These hubs could provide shared access to larger, income-generating solar systems, such as refrigeration units, grain mills, and more. Furthermore, integrating SHS programs into carbon credit markets could allow households and communities to earn credits for avoided emissions. These credits could offset system costs or fund additional sustainability initiatives, creating a feedback loop of environmental and economic benefits.

A critical gap in prior research is the comparison between off-grid systems and traditional grid solutions. Our findings suggest that while grid systems may offer greater reliability for large-scale industrial applications, off-grid solar provides unmatched flexibility and scalability for remote and underserved communities. This distinction highlights the need for tailored approaches to energy equity.

Policy Frameworks

The environmental and economic sustainability of large-scale SHS implementations depends on robust policy frameworks. For instance, increasing battery recycling rates from 10% to 50% can halve lead deposition rates, while achieving 90% recycling—common in industrialized countries—is critical to minimizing environmental risks. Similarly, extending battery lifespans from 3 to 5 years through improved manufacturing quality standards, such as those enforced by the PV Global Approval Process (PVGAP), can significantly reduce lead pollution [4].

However, these environmental policies must be complemented by financial measures to ensure sustainability. Our findings emphasize the need for policies that integrate recycling costs into battery prices and offer targeted incentives through financial institutions.

Additionally, aligning off-grid initiatives with national grid strategies can avoid conflicts and inefficiencies. For example, Bangladesh's SHS program initially succeeded with over 4 million installations by 2013, but a lack of coordination with grid expansion ultimately undermined its long-term sustainability [4].

To ensure scalability, policymakers should prioritize fostering a strong distribution and installer network in rural areas. Addressing bottlenecks in supply chains, providing vocational training, and implementing scalable microfinance structures are essential steps for achieving widespread adoption. Policymakers should also introduce adaptive tariff structures that balance affordability for consumers with cost recovery for operators, as demonstrated by the success of differentiated tariffs in Tanzania.

Strengthening Regulatory Oversight

Regulatory oversight is essential for integrating and enforcing policy frameworks and ensuring the quality, safety, and scalability of off-grid systems. For example, adherence to technical standards like PVGAP ensures product quality, while mandatory recycling programs minimize environmental harm. Simplified licensing processes, such as Tanzania's exemption for mini-grids under 1 MW, have successfully reduced administrative barriers and encouraged private-sector participation [5].

Our findings emphasize the importance of transparent tariff-setting methodologies, such as cost-plus pricing, which balance consumer affordability with operator sustainability. Mechanisms like compensation for stranded assets and interconnection standards further protect investments in mini-grids when national grids expand. Strengthened regulatory enforcement is also critical to maintaining consumer trust; for instance, the lack of quality control for imported solar components in Bangladesh's SHS program declined consumer confidence and limited adoption rates.

To address these challenges, our findings propose the following approach: 1) regulatory bodies must enforce technical standards to ensure quality and reliability, and 2) stakeholders must establish integration guidelines for connecting off-grid systems with existing national infrastructure, ensuring long-term scalability and sustainability.

Integration of Technology with Infrastructure

Integrating advanced technologies with off-grid solar infrastructure is pivotal for addressing persistent challenges such as scalability, reliability, and affordability. Beyond prior work, our findings emphasize the need for hybrid solutions and strategic applications of emerging technologies.

Insights on IoT-Based Systems. IoT-based monitoring systems optimize SHS performance through real-time tracking of battery health, solar panel efficiency, and load consumption. However, our findings suggest that IoT systems can also enable predictive demand forecasting to improve energy allocation and reduce supply mismatches [6]. Adaptive IoT platforms, capable of dynamically adjusting data transmission based on bandwidth availability, are particularly promising for remote regions with intermittent connectivity.

Smart Grids and Hybrid Models. While smart grids are known for integrating off-grid systems with centralized infrastructure, our findings shed light on the underexplored benefit of load prioritization algorithms. These algorithms allow for the intelligent distribution of limited energy supplies to high-priority areas, such as health clinics or schools, during peak demand periods [5]. Additionally, smart grid-enabled hybrid systems can support energy trading among decentralized solar systems, creating micro-markets that empower rural communities.

Data Analytics for Financial Sustainability. Granular energy consumption data can be used to identify underserved households with the greatest need for subsidies or financing support. This enables providers to develop targeted financing models that address affordability gaps more effectively than traditional PAYG schemes.

Bridging Connectivity Gaps. Combining low-power wide-area networks (LPWANs) with satellite systems offers a cost-effective solution for real-time IoT deployment in remote areas. This hybrid connectivity approach reduces reliance on resource-intensive satellite communication alone, making IoT systems more viable at scale.

Gender and Equity Considerations

Our findings reveal persistent challenges and actionable insights in addressing gender inequities through off-grid solar energy. While prior research highlights the transformative potential of solar mini-grids, particularly in education, systemic barriers to women's broader economic empowerment remain underexplored.

For example, the Last Mile Connectivity Project (LMCP) in Kenya highlights how financial exclusion—tied to land and property ownership norms—limits women's access to loans, exacerbating adoption challenges for SHS [2]. High upfront costs further exclude low-income women from benefiting fully from off-grid energy. Measures such as selling treated wooden poles to promote women's economic participation failed to offer long-term opportunities like vocational training in renewable energy fields [1].

Our findings propose actionable solutions, including targeted subsidies, gender-focused financing mechanisms, and robust monitoring frameworks. For instance, disaggregated data can help policymakers design more inclusive programs, while adaptive financing models can enhance women's access to energy solutions. These measures can drive broader economic participation and social inclusion for women in energy-deprived regions.

Summary of Key Recommendations

1. **Community Integration:** Link solar systems to community resources like energy hubs and integrate SHS programs into carbon credit markets to enhance sustainability and amplify benefits.
2. **Policy**: Align off-grid programs with national grid strategies, establish adaptive tariffs, and design scalable financial support mechanisms.
3. **Regulation**: Enforce technical standards, mandate recycling programs, and simplify licensing processes to encourage private-sector participation.
4. **Technology**: Promote IoT-enabled predictive maintenance, adaptive connectivity solutions, and data analytics for targeted financing.
5. **Gender Equity**: Address structural barriers through disaggregated data, targeted subsidies, and vocational training programs for women.

By integrating these recommendations, off-grid solar energy solutions can achieve long-term sustainability and equitable impact in the Global South.

DISCUSSION

The findings of this study underscore the critical role of integrated policies, infrastructure, and technology in ensuring the long-term sustainability and scalability of off-grid systems. They offer important implications for policymakers, practitioners, and researchers. Below, we discuss the broader meaning of these results, their relevance to the community, and opportunities for future research and action.

Key Implications for the Community

Our findings emphasize that off-grid solar energy systems are transformative tools for addressing energy poverty and fostering long-term socioeconomic development. Reliable and sustainable energy access enables communities to improve education, health, and economic outcomes. For example, integrating off-grid systems with community resources amplifies their socioeconomic benefits by creating shared income-generating opportunities, such as community energy hubs for refrigeration, grain milling, or shared lighting [5]. Technologies like IoT systems and smart grids further enhance reliability, optimize energy distribution, and enable data-driven decision-making that empowers local stakeholders [6].

One of the most significant contributions of this work is the identification of structural challenges that limit the scalability and inclusivity of off-grid solar systems, such as financial exclusion and gender inequities. Our findings show that marginalized groups, particularly women, face systemic barriers to accessing energy solutions due to entrenched economic and social inequalities. Targeted interventions—like adaptive financing mechanisms, gender-focused subsidies, and vocational training—can ensure more equitable benefits from these systems. For local communities, these findings underscore the need to prioritize inclusive policies and leverage advanced technologies to maximize the transformative potential of off-grid solar energy.

Our findings emphasize that off-grid solar systems have the potential to transcend their role as standalone energy solutions by acting as catalysts for local economic ecosystems. For example, integrating solar systems with micro-enterprises, such as solar-powered cold storage facilities for agricultural products, can stabilize market prices and reduce post-harvest losses in regions with unreliable energy access [2]. Additionally, community-based energy hubs, leveraging economies of scale, can reduce per capita energy costs and enhance accessibility for marginalized groups. By encouraging local ownership models, such as cooperatives, these hubs can also ensure that economic benefits remain within the community, fostering long-term socioeconomic resilience. These initiatives highlight the critical need for policymakers to adopt community-centric approaches when designing and scaling off-grid solar programs.

Lessons for Researchers

This study provides a comprehensive framework for evaluating off-grid solar energy systems by integrating policy, infrastructure, and technological perspectives. By combining socioeconomic metrics (e.g., income growth, gender equity) with technical analyses (e.g., IoT performance, smart grid integration), it offers a robust approach for assessing the long-term impacts of renewable energy solutions. Researchers should prioritize pilot programs in diverse geographic and socioeconomic contexts, such as testing IoT-enabled hybrid connectivity models or studying microloans targeting women to assess their impact on entrepreneurship and economic resilience.

A critical focus for future studies is the interplay between off-grid solar systems and traditional grid expansion strategies. Understanding how these systems can complement each other is essential for scaling energy solutions effectively. For example, integrating gender-disaggregated data can help refine interventions, ensuring equity and inclusivity in implementation.

Adopting interdisciplinary methodologies is crucial for analyzing off-grid systems comprehensively. Beyond technical evaluations, future research should examine socio-political factors like trust in government programs and cultural attitudes toward renewable technologies. Studies on community-led governance models can provide insights into the role of local leadership in sustaining off-grid systems. Longitudinal research on the economic trajectories of households benefiting from off-grid solar energy can further reveal whether short-term gains translate into sustained development. Incorporating gender-sensitive frameworks will also enable more equitable and impactful energy solutions.

Limitations

While this review provides actionable insights, several limitations must be noted:

Geographic Focus. Although extensive, the review does not equally cover all regions of the Global South. It primarily draws on literature and case studies from specific regions chosen for notable off-grid energy implementation examples within the Global South, such as Bangladesh, Kenya, and Nigeria, and Tanzania. While these regions provide valuable insights into the broad and local challenges and potential of off-grid solar systems, they may not fully capture the full diversity of challenges and opportunities across different geographic and cultural contexts. For example, variations in regulatory environments, cultural norms, and infrastructure availability can significantly impact the feasibility and scalability of proposed solutions. Future research should expand to include underrepresented regions to ensure a more holistic understanding of off-grid solar energy.

Data Consistency and Representation. A significant limitation lies in the inconsistent representation of socioeconomic variables across studies. For example, while some studies focus on financial metrics like income growth or cost savings, others emphasize social indicators like education or health improvements, making direct comparisons difficult. Additionally, the lack of standardized methodologies for measuring long-term impacts limits the ability to draw cohesive conclusions about the broader implications of off-grid solar systems. Addressing this gap would require the development of unified metrics that capture both immediate and long-term outcomes.

Short-Term Focus in Literature. Much of the reviewed literature prioritizes the short-term benefits of off-grid solar systems, such as reduced reliance on kerosene, improved lighting, and short-term economic gains. While these insights are valuable, they do not adequately address long-term impacts such as sustained income growth, intergenerational educational improvements, and the durability of financial and technological interventions. This leaves significant gaps in understanding the long-term sustainability and integration of off-grid solar with national grids.

Technological Assumptions. Recommendations related to IoT and smart grid technologies rely heavily on advanced technologies and infrastructure. These solutions assume the availability of infrastructure and connectivity, which may not hold true in all regions, limiting the practicality of such solutions. Additionally, the costs of implementing and maintaining these technologies are significant, and their affordability for low-income households remains a critical challenge.

Future Work

To address these limitations, we recommend the following areas for future research:

1. **Explore Long-Term Impacts**: Conduct longitudinal studies to evaluate the sustained socioeconomic impacts of off-grid solar systems, including income stability, education, and health outcomes over decades.
2. **Integrate Hybrid Models**: Investigate how off-grid solar systems can complement traditional grid expansion in hybrid energy models, optimizing reliability and scalability while maintaining affordability.
3. **Expand Regional Coverage**: Include more diverse geographic contexts, such as urban areas and smaller island nations, to capture a broader spectrum of energy challenges and solutions.
4. **Strengthen Intersectional Analysis**: Future work should focus on the intersectionality of energy access, considering not just gender but also factors like age, disability, and rural vs. urban divides. Incorporating data that reflects these intersecting identities would provide a more nuanced understanding of how different groups are affected by off-grid solar systems. This approach could also highlight specific barriers faced by marginalized populations, ensuring that interventions are tailored to meet the diverse needs of all community members. Developing policies that prioritize these intersections will ensure more equitable access and opportunities for everyone.

In addition to gender-specific data, incorporating intersectional analyses into policy design could ensure more equitable outcomes across diverse demographic groups. For instance, programs targeting women in indigenous communities must consider cultural practices and local governance structures to maximize adoption rates. In Bolivia, solar-powered education centers have successfully integrated local leaders into decision-making processes, ensuring that energy solutions align with community needs and values [4]. Similarly, empowering women as co-owners of mini-grid projects has shown to significantly increase community buy-in and system sustainability in Kenya [9]. These examples highlight the importance of embedding equity-focused interventions at every stage of off-grid solar deployment, from planning to implementation and evaluation.

At its core, this study sought to answer our research question: *How do policies, infrastructure, and technological integration of off-grid solar energy with national grids impact long-term socioeconomic development compared to traditional energy sources?* Our findings demonstrate that an integrated approach combining policy support, robust infrastructure, and technological innovation is critical for maximizing the potential of off-grid solar systems. Policies that align with national grid strategies, infrastructure that prioritizes scalability and inclusivity, and technologies that enhance reliability and efficiency collectively create a sustainable and equitable energy ecosystem.

Off-grid solar systems are not a replacement for traditional energy sources but a complementary solution to address gaps in energy access and drive socioeconomic development. By focusing on integration, innovation, and inclusivity, off-grid solar systems can play a pivotal role in achieving Sustainable Development Goal 7—ensuring access to affordable, reliable, sustainable, and modern energy for all.

CONTRIBUTION STATEMENT

Ava conceived the initial idea for the research. All members collaboratively refined the concept and formulated the specific research question. Angelina took the lead in designing the methodology for literature review, while Ava curated and synthesized the findings to develop the Related Works section. Likita articulated the findings and contributed to the broader discussion of the literature. Neeharika analyzed and synthesized the collected research into key insights and addressed research objectives cohesively throughout the paper.

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