Assessing the Socio-Economic Impact and Sustainability of Microfinance-Enabled Solar Home Systems in Rural Bangladesh: A Mixed-Method Study (2019–2025)

Fariha Fairouz Proma[1], Md Golam Mubasshir Rafi[1*] and Nowshin Noweer Nisa[1]

[1]Army Institute of Business Administration, Sylhet, Bangladesh

[*]Corresponding Email: gmrafibba-11@aibasylhet.edu.bd

Abstract: The achievement of 99% energy access in Bangladesh by 2025 is a national milestone, but 1-2 million people in remote places still rely on kerosene, resulting in respiratory health hazards and CO_2 emissions. This study investigates assessing the socio-economic impact and sustainability of microfinance-enabled solar home systems in Rural Bangladesh through partnerships led by the IDCOL with Microfinance Institutions such as Grameen Shakti and BRAC. The core objectives are: (1) to evaluate the socio-economic influence of SHS on health in off-grid communities; (2) to identify limitations of current microfinance models amid national grid expansion; and (3) to explore transitions toward AI-integrated and Pay-As-You-Go (PAYG) sustainable energy solutions. Employing a mixed-method approach, the study analyses secondary data from IDCOL reports (2019–2024), World Bank assessments (2018–2023), Grameen Shakti, BRAC case studies and in-depth interviews with users. Findings show that by 2024, over 6 million SHS units generated 250 MW of off-grid solar power, reducing kerosene use by 80–90%, averting 2.7 million tons of CO_2 emissions annually, and improving household health. The study proposes practical innovations expanded PAYG financing, green bonds, strengthened community MFI models, and AI-driven maintenance to overcome costs, battery waste, and grid-integration challenges. This research provides actionable insights for policymakers, MFIs, and retailers. By offering strategies to sustain equitable energy access, it supports Bangladesh's renewable energy goals and delivers practical lessons for other developing countries navigating similar energy transitions.

Keywords: CO2 emissions, SDGs, microfinance, solar home systems, sustainable energy, Bangladesh.

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1. Introduction

1.1. Background of Solar Energy in Bangladesh

Bangladesh has emerged as a global leader in off-grid renewable energy, primarily through its **Solar Home System (SHS)** program. Since the early 2000s, the Infrastructure Development Company Limited (IDCOL) has spearheaded this movement alongside major Microfinance Institutions (MFIs) like Grameen Shakti and BRAC. The initiative was designed to provide basic lighting and electricity to rural households that were not connected to the national grid. By 2024, more than 6 million SHS units have been installed, benefiting approximately 18% of the total population. This program has successfully transitioned millions from hazardous kerosene lamps to clean, reliable solar energy.

1.2. The Shift in the Energy Landscape (The "Alert")

The energy landscape of Bangladesh has undergone a dramatic transformation over the last decade. The government's "Electricity for All" initiative has expanded the national grid at an unprecedented pace, reaching a milestone of 99% energy access by 2025. While this is a massive national achievement, it has created a unique crisis for the existing SHS framework.

As the national grid reaches more villages, many rural households are abandoning their solar systems in favour of grid electricity, which is often perceived as more powerful and cheaper for heavy appliance use. This shift has led to high default rates on solar microloans, leaving MFIs with significant financial burdens. However, an estimated **1 to 2 million people** living in "hard-to-reach" areas (such as char lands and remote coastal regions like Shyamnagar, Satkhira) remain off-grid and will likely remain so for the foreseeable future. For these populations, SHS is not a luxury but a fundamental necessity for survival and development.

1.3. Socio-Economic and Environmental Implications

The reliance on kerosene in off-grid areas is not just an energy issue; it is a public health and environmental crisis. Kerosene lamps emit harmful black carbon and CO2, leading to respiratory diseases, especially among women and children. Research indicates that SHS adoption can reduce kerosene use by up to 90%, averting millions of tons of CO2 emissions.

Beyond health, the socio-economic impact is profound. Access to solar light extends the productive hours of the day. Children can study for an additional 1–2 hours at night, and small rural businesses can remain open longer, directly increasing household income. However, the sustainability of these benefits is currently threatened by two major factors:

1. **Financial Barriers:** The traditional ownership-based microfinance model is struggling to stay viable.
2. **Environmental Hazards:** The lack of a formal recycling system for lead-acid batteries (ULAB) has led to informal recycling, which poses severe toxic risks to soil and water.

1.4. Importance of Energy Access

The world bank report emphasises that reliable electricity access via SHS is transformative for rural Bangladesh. It delivers immediate gains in health (reduced respiratory and gastrointestinal illnesses, lower fire risks from kerosene), economic opportunities (extended work hours, mobile charging, rural businesses), gender equity (improved women's mobility, security, decision-making, and reduced domestic burden), and poverty reduction (kerosene savings redirected to nutrition and assets). The programme saved 4 billion litres of kerosene (2003–2021) worth US$908 million (2003–2018) and avoided 9.6 million tons of CO_2. It reached 20 million people (14% of the population), providing safer, brighter lighting and access to information via TV/radio.

1.5. Current SHS Policy Framework and Implications

IDCOL's SHS programme (launched 2003 under the Rural Electrification and Renewable Energy Development Project) used a market-based microfinance model with declining subsidies and strong NGO/MFI partnerships. By 2018 it had installed 4.1 million systems (163 MW).

Post-2018 shift: Rapid grid expansion (BREB connections rose 280% from 2015–2019) caused commercial SHS sales to collapse (from 861,000 in 2013 to just 3,455 in 2018). The policy pivoted to government give-away programmes under IDCOL management and debt restructuring (0% interest, repayment extended to 2026).

Implications: The model successfully bridged the pre-grid gap but created market disruption in remote areas. It left residual energy poverty (1–2 million people still off-grid) and highlighted the need for hybrid off-grid solutions, PAYG models, and better grid–SHS coordination to avoid stranding remote communities.

1.6. Policies Adopted and Results

Policy	Details Adopted	Key Results
Subsidies	Grants declined from 19% (2003) to 5% (2017) of the system cost	Cost per fell from US$12 to <US$5
Financing	Microfinance loans (12–16% interest, 1–3 years); IDCOL refinancing to POs	Repayment rates >95% initially; later defaults led to restructuring
Quality standards	The Technical Standards Committee enforced warranties and testing	90% batteries are still operable after 5 years

Figure 1. Policy adopted and results

1.7. Who Are the Beneficiaries?

Primary: Rural poor households in off-grid and hard-to-reach areas (initially 15 million unelectrified households in 2003).

Demographics: Women (greater mobility, security, and decision-making power), children (education gains), and low-income families.

Scale: ~4.1 million households (~20 million people, including 10 million children).

Geographic focus: Highest penetration in Barisal (39%), Sylhet (30%), and Chittagong; lower in grid-dense regions like Rajshahi.

1.8. Research Gap and the Need for a Mixed-Method Study

Most previous studies on SHS in Bangladesh focus either purely on the statistical expansion of the technology or the technical efficiency of solar panels. There is a significant gap in understanding the **real-time human experience** during this transition phase (2019–2025). This research addresses this gap by employing a **mixed-method approach**. By combining secondary data from IDCOL and the World Bank with primary qualitative interviews (such as the experiences of anonymous users), this study provides a holistic view of the current crisis and future opportunities.

1.9. Research Questions

To guide this investigation, the study addresses the following questions:

1. How has the adoption of SHS influenced the quality of life, specifically in health and education, for rural households?
2. What are the primary factors causing the shift from ownership-based solar models to national grid dependency?
3. To what extent can modern technology (AI and PAYG) mitigate the current maintenance and financial barriers of solar systems?

1.10. Research Objectives

The primary objectives of this study are:

1. To evaluate the socio-economic influence of SHS on education and health in off-grid communities.
2. To identify the limitations of current microfinance models in the face of national grid expansion.
3. To explore the transition towards AI-integrated and Pay-As-You-Go (PAYG) sustainable energy solutions.

2. Literature Review

The success and challenges of Solar Home Systems (SHS) in Bangladesh have been extensively documented. According to **Samad et al. (2013)**, SHS provided a foundational shift in rural livelihoods by increasing study hours for children and improving household productivity. Building on this, **Samad et al. (2013)** highlighted that SHS adoption led to sustained reductions in personal exposure to PM2.5 and black carbon, significantly improving respiratory health compared to traditional kerosene use.

However, the rapid expansion of the national grid has altered the sector's dynamics. Reports from **IDCOL (2024)** and **World Bank (2023)** indicate that while grid access is a national goal, it has created financial strain for microfinance institutions (MFIs) as many users struggle to pay for redundant solar systems. **Sparkassenstiftung (2021)** emphasized that current microfinance models need to evolve to remain viable in a grid-connected landscape.

Environmental sustainability remains a critical gap. **Pure Earth (2020)** identified severe risks from informal lead-acid battery (ULAB) recycling, suggesting a need for formal e-waste management. To address these operational and environmental issues, recent literature points toward technological integration. Studies in **Energies (2023)** suggest that **Artificial Intelligence (AI)** can optimize maintenance, while **Pay-As-You-Go (PAYG)** models, as discussed in recent global energy transitions, offer a more flexible financial framework for low-income households. This study bridges the gap between historical success and future technological needs by evaluating the socio-economic transitions from 2019 to 2025.

3. Methodology

This study adopts a **mixed-method research design** to triangulate quantitative macro-trends with qualitative human experiences. This approach ensures a comprehensive understanding of the socio-economic impacts and sustainability of Solar Home Systems (SHS) in Bangladesh (Creswell & Plano Clark, 2018).

3.1. Quantitative Data Collection (Secondary Source)

The study utilizes secondary data from 2019 to 2025 to track macro-level trends and evaluate the overall performance of the SHS program. Key data sources include:

- **IDCOL Annual Reports:** To analyze installation rates, loan disbursement trends, and the geographical reach of solar programs across Bangladesh.
- **World Bank Assessments:** To evaluate environmental impacts, specifically CO2 emission reductions and large-scale economic returns on investment.
- **MFI Case Studies (Grameen Shakti & BRAC):** To understand the financial health of the solar microfinance sector and the operational challenges faced by partner organizations.
- **Academic Literature:** Peer-reviewed journal articles focusing on policy shifts, grid expansion, and the e-waste (ULAB) challenge (e.g., Samad et al. (2013); Pure Earth, 2020).

3.2. Qualitative Data Collection (Primary Source)

To capture the real-time socio-economic impact at the household level, primary qualitative data were collected through semi-structured interviews.

- **Sampling:** A purposive sampling method was used to select participants from off-grid or recently electrified regions (e.g., Shyamnagar, Satkhira). The sample included users who have used SHS for over five years or have transitioned to the national grid.
- **Interviews:** Semi-structured interviews were conducted with rural farmers and small business owners . These discussions provided deep insights into changes in children's education, household health, and daily income.
- **Thematic Analysis:** The interviews were analyzed to identify recurring themes, such as "improved study environment," "respiratory health benefits," and the "financial burden of ownership" amid grid expansion.
- **Data Management Tool:** The qualitative interview transcripts and field notes were managed and coded using **NVivo 12** software. This tool facilitated a systematic thematic analysis, allowing for the efficient organization and categorization of participant responses into key socio-economic and operational themes.

3.3. Data Triangulation

To ensure the validity and credibility of the findings, a process of **data triangulation** was employed. This involved cross-referencing primary user experiences (qualitative) against the statistical trends found in institutional reports (quantitative). By verifying household-level benefits against national-level data, the study provides a robust and reliable basis for its conclusions.

4. Results and Discussion

The findings of this study are categorized into socio-economic outcomes and the operational challenges faced by the SHS program during the 2019–2025 period.

4.1. Socio-Economic Impact: Health and Economic Productivity

The transition from kerosene lamps to SHS has produced measurable benefits in household health and income, as evidenced by both primary interviews and secondary reports.

- **Health Improvements:** Traditional kerosene lighting is a primary source of indoor air pollution. Primary qualitative data from field interviews confirm that switching to SHS has significantly reduced respiratory discomfort. Households reported a cleaner indoor environment, which aligns with findings from **Samad et al. (2013)** regarding reduced black carbon exposure.
- **Extended Productive Hours:** One of the most significant outputs is the increase in evening productivity for small rural businesses. Participants who run small-scale shops or home-based businesses reported that reliable solar lighting allowed them to remain open longer, directly impacting their daily earnings. *"Having solar light allowed me to keep my shop open after evening, which directly increased my monthly income."* – **A respondent from Shyamnagar, Satkhira.**
- *"Having solar light allowed me to keep my shop open after evening, which directly increased my monthly income."* – **A respondent from Shyamnagar, Satkhira.**

Field interviews with respondents in Satkhira validate the operational efficiency of the MFI service network, noting that technical support remains available upon request. However, the high cost of battery replacement is identified as the most critical barrier. While installment-based replacement plans exist, the sudden financial burden of a damaged battery remains a primary concern for low-income users, often outweighing the benefits of initial energy access.

- **Kerosene Cost Savings:** Secondary data from **IDCOL** indicates an 80-90% reduction in kerosene consumption per household. This shift translates into direct financial savings, allowing families to allocate funds toward other essential household needs. Beyond health and savings, the transition to solar energy has significantly advanced **gender equity** and household safety. Access to reliable lighting has improved women's mobility and sense of security at night while reducing the risk of accidental fires associated with kerosene lamps. These qualitative gains have empowered women in off-grid communities, enhancing their decision-making power and reducing domestic burdens.

- **4.2. Financial Challenges: The Grid Expansion Collision**

While the SHS program was highly successful in off-grid eras, the rapid expansion of the national grid has created a "collision of policies."

- **Default Risks in Ownership Models:** The traditional microfinance model relies on a long-term ownership-based installment system. However, as grid electricity which supports heavy appliances like fans and televisions, reaches rural areas, users often lose interest in maintaining solar installments.
- **Economic Redundancy:** Many households now view SHS as a redundant backup rather than a primary energy source. This perception shift has led to financial strain on both the users and the MFIs (Grameen Shakti, BRAC), as loan recovery rates have declined since 2021. A significant shift in the SHS landscape occurred after 2018. As the national grid expanded rapidly with connections rising by 280% between 2015 and 2019 commercial SHS sales experienced a sharp decline, dropping from 861,000 units in 2013 to just 3,455 in 2018. This forced a policy pivot from market-based microfinance models toward government-led 'give-away' programs (e.g., TR/KABITA), creating new challenges for debt recovery and long-term market sustainability.

- **4.3. Environmental Sustainability and Battery Waste**

A critical but often overlooked output is the management of e-waste, specifically

Lead-Acid Batteries (ULAB).

- **Informal Recycling Risks:** Despite the environmental benefits of solar energy, the lack of a formal recycling framework poses a threat. Secondary reports from **Pure Earth (2020)** suggest that informal recycling of solar batteries leads to soil and water contamination.
- **The Need for Systematic E-Waste Policy:** Current microfinance models focus heavily on the distribution of solar panels but lack a robust "take-back" policy for aging batteries, which is essential for long-term environmental sustainability.

- **4.4. Proposed Innovation: Transition to AI and PAYG**

To mitigate the financial and maintenance barriers, the study explores modernized service models:

- **Pay-As-You-Go (PAYG):** This model allows users to pay for energy as a service rather than owning the hardware, reducing the initial financial burden and default risks.
- **AI Integration:** Integrating **Artificial Intelligence (AI)** for predictive maintenance can monitor battery health and system performance remotely. This ensures that populations in "hard-to-reach" areas receive uninterrupted service without high manual maintenance costs.

5. Discussion and Synthesis

The discussion of findings provides a deeper understanding of the relationship between microfinance mechanisms and solar energy adoption during Bangladesh's national grid expansion.

5.1. Triangulation of Qualitative and Quantitative Findings

A core strength of this study is the alignment between household-level experiences and macro-level statistical trends. For instance, the **IDCOL (2024)** reports indicate an 80-90% reduction in kerosene dependency, which is strongly validated by our primary qualitative interviews. Respondents consistently highlighted that the transition was motivated not just by financial savings on kerosene but by the perceived improvement in indoor living standards.

5.2. The "Grid-Solar" Paradox

The analysis reveals a unique paradox: while national grid expansion represents progress, it simultaneously threatens the financial viability of existing solar infrastructure. Quantitative data shows a decline in new SHS installations since 2021, which our interviews explain as a shift in user perception. Many households now view SHS as an "inferior" energy source compared to the grid, leading to a psychological and financial detachment from solar micro-loan commitments.

5.3. Comparison with Previous Literature

Our findings support the work of **Samad et al. (2013)** regarding health benefits but add a new dimension concerning the "sustainability crisis." Unlike earlier studies (e.g., **Samad et al., 2013**) which focused on the rapid growth phase of SHS, this research identifies the "transition phase" challenges. It highlights that the socio-economic benefits of SHS are being overshadowed by the lack of institutional support for battery waste and the high cost of maintenance in the face of cheaper grid electricity.

6. Policy Recommendations

Based on the findings of this study, the following strategic recommendations are proposed to ensure the sustainability of rural energy access:

- **6.1. Mandatory E-Waste Management Policy:** The government and IDCOL should implement a mandatory "Take-Back" policy for expired lead-acid batteries. Establishing formal recycling centers will prevent informal recycling hazards and protect rural soil and water quality.
- **6.2. Transitioning to Service-Based Models (PAYG):** MFIs should move away from the traditional ownership model toward a Pay-As-You-Go (PAYG) framework. This will reduce the initial financial burden on low-income households and lower the risk of loan defaults as the national grid expands.
- **6.3. Integration of Smart Monitoring:** Incorporating AI-driven remote monitoring systems can enhance maintenance efficiency. Predictive maintenance will allow MFIs to identify technical issues before the system fails, ensuring long term reliability for off-grid populations.
- **6.4. Grid-SHS Hybrid Framework:** Policymakers should design a framework where SHS acts as a reliable backup to the national grid during load-shedding or natural disasters, ensuring uninterrupted energy security for rural households.

7. Limitations and Future Research

Although this study provides critical insights into the SHS landscape in Bangladesh, it has several limitations:

- **Geographical Scope:** Due to resource and time constraints, primary qualitative data collection was limited to specific regions (e.g., Shyamnagar, Satkhira). Therefore, the findings may not fully capture the diverse socio-economic realities of off-grid populations in other parts of the country, such as the northern char lands or Chittagong Hill Tracts.
- **Sample Size:** The number of primary interviews was limited. A larger and more diverse sample size would have allowed for a more robust generalization of the results.
- **Data Dependency:** The quantitative analysis relies heavily on secondary data from institutional reports. While reputable, these sources may have inherent reporting biases or time lags.

Future Research Directions:

Future studies should aim for a nationwide longitudinal analysis to assess the long-term impact of informal battery recycling on soil and water toxicity. Additionally, further research is needed to evaluate the cost-effectiveness of AI-integrated PAYG systems compared to national grid expansion in extremely remote and disaster-prone areas.

8. Conclusion

This research has evaluated the socio-economic impacts and sustainability of microfinance-enabled Solar Home Systems (SHS) in rural Bangladesh during a period of rapid energy transition (2019–2025).

The study concludes that while SHS has been a revolutionary tool for improving household health and increasing small-scale economic productivity, the traditional ownership-based microfinance model is now facing a "policy collision" with national grid expansion. To prevent the abandonment of solar infrastructure and ensure energy equity for the remaining off-grid populations, a strategic shift is required.

By transitioning from hardware ownership to service-based models like **Pay-As-You-Go (PAYG)** and integrating **AI-driven maintenance**, stakeholders can ensure long-term energy sustainability. Ultimately, this research provides a roadmap for policymakers and MFIs to refine their strategies, ensuring that no household is left behind in Bangladesh's journey toward a green energy future.

Conflict-of-Interest Statement

The authors declare that they have no conflicts of interest relevant to this study.

Declaration of AI Usage

During the preparation of this work, the author(s) used Google Gemini exclusively for language refinement and editing to ensure clarity and grammatical accuracy. The conceptualization, data analysis, and findings are the original work of the author(s)**.**

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