Addressed Topic/s: 1.3 Mini-grids / 2.4 Customer perspective / 3.4 Village energy / 4.6 Success & failure factors

A socio-technical analysis of hybrid mini-grid performance in rural Benin: linking customer archetypes, load profiles, and outage dynamics

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Introduction

Achieving universal access to electricity is a critical global challenge, particularly in remote, rural communities where decentralized solutions like mini-grids have emerged as one of the most adaptable technologies to bridge this gap. However, most studies on mini-grids evaluate energy consumption or reliability in isolation, missing the socio-technical interactions that drive demand, downtime, and revenue. This study develops a socio-technical framework combining high-resolution (15-min) smart meter data and household surveys from two hybrid solar mini-grids (Samionta and Gbowele) in Benin. By linking load profiles to customer archetypes, the analysis offers a holistic view of performance from both supply and demand sides.

Methodology

Eighteen months of smart-meter records (2024-2025) from 46 surveyed households are combined with socio-economic survey data. Customers are categorized into 4 income-based archetypes, enriched with data on family size, construction materials, economic activities and appliance ownership. Load profiles are then computed per archetypes as mean and median daily curves, with outliers identified as customers consuming more than the standard deviation above their group average.

System reliability is assessed by detecting system-wide outages (periods with no recorded consumption across the village), from which System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) are calculated. Customer-side reliability is separately analyzed by detecting credit-related disconnections, defined as zero-consumption periods resolved by a subsequent mobile payment. The events are quantified through new indices: CIFI (Customer Interruption Frequency Index) and CIDI (Customer Interruption Duration Index). This two-track method distinguishes technical failures from affordability-driven interruptions.

Results

Household profiling shows clear socio-economic stratification. Higher-income households display consistent evening peaks driven by ICT and entertainment appliances, while lower-income groups rely almost exclusively on lighting. A few productive-use customers emerge as outliers, consuming up to above 20 kWh/day and shaping aggregated demand.

System-level reliability diverges sharply between sites. Gbowele has a SAIFI of 189 outages/year, with SAIDI of 32 days/year (7.3% downtime) and a maximum outage duration of 4.6 days. Samionta, by contrast, has a SAIFI of 16 outages/year and SAIDI of 2.8 days/year (0.5% downtime). On the demand side, credit-related disconnections are nearly similar: 97.6% of customers in Gbowele (860 events) and 97.8% in Samionta (541 events) were affected. Regarding reliability indices, there is a CIFI of 21 events/client in Gbowele and 12 events/client in Samionta, a CIDI of 12.8 days/client and 21.4 days/client, respectively. Average event durations are 14.6 hours in Gbowele and 1.7 days in Samionta, with extremes up to 27.8 days and 152 days respectively. About 9% of all zero-consumption points are attributable to lack of credit in both sites, with the five most-affected clients representing nearly 40% of events.

Conclusions

This socio-technical analysis demonstrates that accomplishing SDG7 requires interventions on both the supply and demand sides. Although Gbowele and Samionta show contrasting SAIFI/SAIDI values, credit-related disconnections, accounting for about 9% of zero-consumption, affect nearly all users, with CIDI exceeding 21 days. This indicates that affordability-driven outages can be as critical as technical failures in shaping service reliability. To ensure equitable energy access, future mini-grid design must jointly optimize for technical uptime and financial accessibility, supported by adaptive tariff schemes and tailored customer engagement.

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