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Powering inclusive growth: Measuring electricity impacts on micro, small, and medium enterprises in Sierra Leone

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Title

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Executive Summary

Electricity is fundamental to economic growth, yet in sub-Saharan Africa, power outages and poor voltage quality are not only persistent but significantly constrain business growth and productivity and are estimated to cost the region 1-5% of GDP (Rentschler et al, 2019). In low-income countries (LICs) like Sierra Leone, the cost of poor PQR is not only economic but closely tied with environmental and social inequalities: as 80% of those who experience chronically poor power quality and reliability (PQR) live in peri-urban and rural areas — and operate the micro, small and medium enterprises (MSMEs) that deliver more than 50% of job creation and drive economic growth.

Empirical research has documented the adverse effects of poor PQR on MSME output and costs in several low- and middle-income countries (LMICs) (e.g., Pakistan, Ghana, and Nigeria via the World Bank Enterprise Survey). However, the mechanisms linking poor PQR to MSME productivity in LICs remain poorly understood largely due to limited or non-existent granular, real-time measurements needed to capture the nature, as well as the spatial and temporal variations, of PQR in these countries. As the Sierra Leone government and development partners prioritise industrialisation and private-sector-led growth, understanding the nature, scale, and costs of poor PQR is pivotal for designing targeted energy interventions.

This study addresses current data gaps around PQR issues and their impacts on MSMEs by conducting large-scale, city-wide electricity monitoring in Freetown, Sierra Leone. Specifically, we investigated two research questions:

- What is the nature, scale, and variation of PQR among MSMEs in urban and peri-urban Freetown?
- What role does PQR play in MSME operating costs and business resilience strategies?

To answer our research questions, we leveraged *n*Line's GridWatch Suite—a novel PQR remote-monitoring solution that provides high-resolution customer-level sensing of voltages, outages, frequency, and transient power quality events. The GridWatch Suite combines *n*Line's GridWatch sensor with a deployment management system, advanced data processing, and powerful web-based real-time data visualizations. GridWatch sensors were deployed in 48 businesses connected to 12 transformers across Freetown to collect real-time PQR measurements—including power outages (frequency and duration) and voltage and frequency levels—over a 9-month period from November 2024 through July 2025. Using machine-learning models grounded in power systems, sensor-collected measurements were transformed into PQR key performance indicators showing grid health and performance in Freetown. Based on the collected data, we: (i) characterised the nature, scale, and variance in PQR experienced by MSMEs across Freetown, identifying areas where power quality and outages may be worse, and adaptive capacity is lower; (ii) assessed the operational impacts of systems-level voltage disturbances—such as low voltage, sags, and surges—on appliance functionality across monitored businesses; and (iii) quantified the estimated cost of outages for the utility.

Key Findings

Spatial inequities in power quality and reliability across Freetown. Our analysis reveals significant spatial disparities in the nature and scale of PQR across Freetown's grid, with a distinct east–west divide. MSMEs located in the east consistently experienced substantially longer duration of outages than those in the west. For example, in Hastings, quarterly outage durations were nearly seven times higher than those recorded in the Central Business District. Outage typologies also differed by geography: the eastern portion of the grid was disproportionately affected by large-scale, high-to-medium voltage (HV-MV) interruptions, while outages in the west were more frequently localized, typically occurring at the distribution low-voltage level. This pattern suggests that the observed reliability challenges are rooted in both structural conditions of HV-MV transmission infrastructure and in LV inefficiencies.

Voltage quality impacts MSME operations and finances. Voltage performance issues were high and varied across monitored communities. MSMEs located in the east experienced chronic undervoltage conditions. In Hastings, for example, monitored MSMEs spent an average of 6.6 hours daily undervoltage—deviations which constrained the operational functioning of electrical appliances. Likewise, MSMEs in Allen Town experienced voltage excursions that were consistently associated with appliance damages. Replacement or repair costs for affected appliances were reported to exceed several hundred Leones (SLE) per incident, representing a disproportionate financial burden for MSME operating with limited liquidity. In contrast, MSMEs in the west, such as in Lumley, benefited from stable voltage supply levels, with service conditions remaining close to the nominal 230V standard.

The monetary costs of outages for the Electricity Distribution and Supply Authority (EDSA) are substantial once scaled across a broader sample of MSMEs. The estimated monetary costs of outages to EDSA were found to be significant when assessed in terms of unserved energy. For the 48 monitored MSMEs, the cumulative estimated cost of unserved energy—derived by multiplying the kilowatt-hours (kWh) not delivered during outage periods by the applicable tariff rate—was approximately USD 9,500 over the monitoring period. Extrapolating this figure to markets in Freetown, and assuming similar outage exposure and consumption characteristics, our scenarios estimate aggregate losses in the order of several hundred thousand USD. These losses not only correspond to foregone electricity sales for EDSA, they directly diminish EDSA's revenue base, with significant implications for the utility's fiscal sustainability, particularly in the context of an already constrained financial environment.

In conclusion, we find that the spatial and operational PQR inequities experienced by MSMEs not only reinforce existing patterns of urban economic inequalities but have significant implications for grid-wide performance and economic resilience. Addressing these challenges requires: (i) targeted and spatially responsive grid planning and network efficiency investments, and (ii) a revision of existing institutional logics around grid operations and regulations in a way that centres MSME interests, productivity, and economic performance to ensure that both EDSA and MSMEs profit from efficiency improvements. Beyond Sierra Leone, our findings offer wider lessons to other LICs across sub-Saharan Africa with similar PQR constraints.

1. Background

Reliable and high-quality electricity are congruent to economic and industrialisation goals. In low-and-middle-income countries (LMICs), poor power quality and reliability (PQR)—originating from aging low voltage (LV) networks and manifesting as persistent grid outages and voltage fluctuations—diminish economic growth. In sub-Saharan Africa (SSA), PQR-driven inefficiencies contribute to the erosion of industrial competitiveness and are estimated to cost the region 1-5% of GDP (Rentschler et al, 2019). Micro, small and medium enterprises (MSMEs)—which form the backbone of the private sector, deliver job creation and drive economic growth across the region—are often left to rely on costly diesel generation—estimated at $59 billion USD annually. The use of diesel not only undermines the financial viability of utilities but creates a negative feedback loop in which declining utility revenues further constrain investment in grid maintenance and upgrades, perpetuating systemic unreliability.

Several scholars have begun to document the adverse effects of poor PQR on MSME output and productivity in LMICs in SSA including Nigeria, Ghana, and Tanzania (Allcott et al., 2016; Avordeh et al 2024). In contrast, empirical evidence on the impacts of poor PQR on LICs like Sierra Leone—where MSMEs drive economic growth and deliver over 50% of job creation—remains sparse. This gap in evidence is concerning given that 22 of the world's 26 LICs are in SSA, many of which face chronic PQR issues.

To support MSME productivity and ultimately catalyse current visions of industrialisation across LICs, energy stakeholders urgently need to understand why, where, and how grids are failing. Unfortunately, granular, real-time measurements capturing the nature and spatial and temporal variations of PQR at the LV-level in LICs are non-existent. The consequence? Policymakers and researchers in LICs lack the data to accurately evaluate the effects of poor PQR on firm-level productivity or design targeted PQR investments that enable industrial growth, reduce poverty, and promote industrialisation. Without granular PQR data, policy and investment decisions risk being based on inferences from more advanced economies that potentially overlook the unique constraints facing MSMEs in SSA's most vulnerable economies.

This study addresses these data gaps around PQR issues and their impacts on MSMEs by conducting large-scale, city-wide electricity monitoring in Freetown, Sierra Leone. To operationalize our objective, we leveraged a novel, remote-monitoring system—GridWatch—to collect direct PQR measurements in businesses across Freetown. Using GridWatch, we investigated two research questions:

- What is the nature, scale, and variation of PQR among MSMEs in urban and peri-urban Freetown?
- What role does PQR play in MSME operating costs and business resilience strategies?

By answering the above questions, our study offers both scientific and policy contributions. First, this study provides a never-before-collected, state-of-the-art comprehensive longitudinal dataset that advances research on the role of poor PQR on MSME in LICs. Most studies on the role of

PQR on MSME productivity have been conducted in LMICs and were largely based on surveys (Owusu et al, 2022, Maende & Awanga 2020, Abdisa 2018). Our methodology leverages direct PQR measurements using our novel remote-monitoring system, GridWatch. GridWatch is a generational advancement over recall-based survey methods and deviates (largely phone-ins from customers on outages) from utility-collated data. GridWatch has successfully supported power quality audits of bulk grids in Ghana, Kenya, and Senegal. In Ghana, GridWatch combined with enterprise surveys showed that reliability experienced by firms is seven times worse than reliability statistics reported by the Electricity Company of Ghana (Mathematica, 2022). As such our use of GridWatch addresses the longstanding need for high-resolution and precise data that not only tracks and identifies PQR impacts on business services in underserved areas but enables transformative policy actions.

Second, this study responds to a critical policy need in Sierra Leone, where the government, in collaboration with development finance partners, is scaling up investments in renewable electricity systems (RES) to mitigate the economic impacts of poor PQR. Over the next four years, an estimated $200 million USD will be spent on electrification in Sierra Leone (State House, 2025). The effective design and targeting of these interventions, however, are hindered by the lack of sub-national and national data on PQR. In the current data vacuum, millions of poor households and businesses—who are often the most affected by poor PQR—remain largely invisible in energy planning processes. This limits the potential for RES investments to deliver inclusive economic benefits. By generating timely, granular, and contextually grounded measurements of PQR, this study provides critical evidence to inform more equitable energy planning.

To provide a conceptual foundation for this study, the next section explores existing research which captures the interactions between PQR and MSME productivity in SSA. We explore current gaps within the existing literature and conclude with a quick summary on how our approach addresses the observed gaps.

2. Literature Review: The Economic Costs of Poor Grid Reliability in SSA

Reliable and high-quality electricity is indispensable for driving economic development, growth, and structural transformation. In LMICs, electricity systems are often characterized by poor PQR that manifests as chronic outages and voltage fluctuations—which directly constrain firm performance, increase operating costs, and reduce competitiveness (Fisher et al 2015, Abeberese, 2017). According to Xiao et al (2022)'s analysis of the World Bank Enterprise Survey of 119 countries, poor PQR significantly reduces total factor productivity and is strongly correlated with reduced business investment, job creation, and firm-level productivity, especially in firms in LMICs.

In SSA, the economic cost of poor PQR unfolds at macroeconomic and microeconomic levels. At the macro level, electricity-reliant industries such as steel, cement, and large-scale manufacturing suffer from chronically reduced capacity utilization and competitiveness in outage-prone urban centres (Cole et al, 2018). In Tanzania, for example, around one-third of firms reported equipment damage as a direct result of outages (Moyo, 2013). In Ghana, during periods of severe outages, firms moved away from electricity-intensive production methods and increased outsourcing—actions that raised total production costs (Abeberese et al, 2021). Panel data from Tanzania, Ethiopia, and Mauritius also link frequent outages with declines in firm revenue, value-added, and output per worker, with observed productivity losses ranging from 4 to 20% (Mensah, 2024, Gurara & Tessema, 2018, Cole et al, 2018) .

At the microeconomic level, the impacts of poor PQR are often more severe and entrenched for MSMEs. The International Financial Corporation (IFC) estimates that MSMEs lose roughly USD $2–32 per kWh during outages (IFC, 2019). While large firms employ large-scale self-generation as a coping strategy (51% of firms in SSA report owning or sharing diesel backup generators), for many MSMEs the cost of acquiring a generator is detrimental and sometimes prohibitive (World Bank, 2025). PQR-induced reliance on backup generation exacerbates inequality: large firms achieve economies of scale on generator costs (lower $/kWh), whereas for MSMEs each kWh of backup power is very costly. The high upfront cost of backup generators, coupled with narrow operating margins, means that outages consume a disproportionately large share of MSMEs' productive output (IFC, 2019). Off-grid renewables have emerged as a partial solution to mitigate PQR issues; nevertheless, these systems still depend on expensive battery storage systems, which means they remain cost prohibitive for many smaller firms.

Improving PQR can unlock substantial socio-economic gains. Empirical evidence from Cole et al. (2018), using cross-country firm data, predicted that sales in 14 SSA countries would jump by ~85% if outages fell to South African levels. Kaba & Tchana, (2024) found that medium-sized manufacturers with reliable connections were able to raise export share by 5–12 percentage points and better reliability cuts MSMEs' need for diesel generators, lowers harmful emissions, and improves utility finances. In response to these research findings, recent electrification efforts across SSA have pivoted toward expanding generation capacity and extending grid coverage. However, these infrastructure upgrades typically target connectivity and often neglect service quality and overall network performance. The impact? utilities, policy makers, and researchers can neither truly assess the impacts of new investments in improving PQR for MSMEs nor verify that newly added capacity reaches consumers reliably.

To bridge the above data gaps, a range of valuation methodologies have been employed in the literature to quantify the economic benefits associated with improved PQR for MSMEs as well as for society more broadly. Among the most widely utilized are the Value of Lost Load (VoLL) approach, which measures consumers' willingness to pay to avoid electricity outages, and the Customer Damage Function (CDF), which maps outage attributes—such as frequency, duration, and temporal occurrence—onto the monetary losses borne by MSMEs and households (Akpeji et al., 2020). While both VoLL and CDF provide valuable customer-facing insights, their scope is largely confined to the microeconomic level and thus insufficient for capturing the wider, sectoral repercussions of electricity outages.

Beyond MSME-related economic losses, an equally critical dimension is the costs borne directly by utilities in relation to unserved energy. Previous studies have shown that utilities face significant financial impacts from outages, including lost revenues, increased operational expenses, and reputational damage (Trimble et al, 2016, Abeberese, 2017). Furthermore, reliability improvements through grid reinforcements have been shown to yield tangible economic benefits not only for consumers but also for utilities themselves, by reducing exposure to compensation claims, regulatory penalties, and the long-term erosion of customer trust (Trimble et al, 2016). In this context, the cost of unserved energy has emerged as a widely accepted and policy-relevant metric, offering a systematic framework through which utilities can quantify the economic benefits of reliability enhancements.

2.1 Methodological Limitations within Existing Approaches

Methodologically, studies that leverage VoLL and CDF and those that quantify the monetary cost/benefits of reducing outage interruptions for utilities remain largely reliant on macro-level recall-surveys (e.g., the World Bank Enterprise Surveys). These surveys typically ask binary questions around “hours of access” and “cost of fuel use on profitability” and verify reliability from utility-collated data—which are known to be unreliable (Taneja, 2018). Alongside surveys, these studies often rely on indirect proxies such as changes in electricity generation or simulations that compute the marginal cost of unserved energy based on supply-demand balances. While surveys and simulations are useful, they suffer from critical limitations: (i) Many reliability issues are not directly perceptible to users and thus elude recall-based surveys; (ii) generation data does not accurately reflect delivered electricity due to network losses; (iii) both surveys and proxy data are typically collected at coarse temporal scales, obscuring short-run variation that is essential for addressing endogeneity; and (iv) even when aggregated utility data is used, they sometimes understate the frequency and severity of power-quality issues, which obscures the lived experiences of MSMEs and the real costs for utilities (Osunmuyiwa et al 2025).

Despite anecdotal and pilot evidence that poor voltage quality imposes substantial costs on firms by damaging equipment, lowering efficiency, and increasing operational uncertainty, existing studies primarily examine power outages; only a few studies (e.g., Osunmuyiwa et al 2025, Berkouwer et al, 2025) focus on voltage quality. Evaluating voltage impacts on MSMEs is particularly important. For example, voltage sags and sustained undervoltage and overvoltage conditions can potentially damage equipment, and MSMEs often depend on appliances and equipment that are more sensitive to voltage issues than simple household appliances. Survey evidence from Accra, Ghana highlights the severity and prevalence of voltage-related challenges—one-third of firms report equipment damage, with average repair or replacement costs of about USD $41, and view voltage-driven costs not only as an operational constraint but also a source of significant financial burden due to the need for costly protective devices (Berkouwer et al, 2025). Many of these firms were willing to increase monthly electricity spending by about 10% to eliminate voltage fluctuations, and by roughly 19% to eliminate both fluctuations and outages, indicating a clear willingness to pay for quality improvements. Even when MSMEs use renewable energy solutions or inverters to mitigate outages, many inverters are designed to trip offline when they detect sufficient voltage deviations. Local voltage quality issues can cause frequent “nuisance” trips that reduce the value of rooftop solar and can even trigger wider system instabilities (Katiraei et al, 2015). Without examining the impacts of voltage quality, claims about electricity quality remain incomplete and misleading, thereby weakening both scholarly understanding and policy responses to the challenges MSMEs face.

2.2. Our Approach

We argue that to effectively address the research, methodological, and data gaps described above, it is imperative to record and quantify the effects of outages and voltage deviations on MSMEs in real time at the low-voltage (LV) network level. The adoption of real-time remote-sensing technologies provide a critical methodological advancement by generating temporally and spatially accurate datasets. This approach not only facilitates comparability across contexts and over time but also enables the transparent translation of outage and voltage events into internationally recognized power system performance indices—such as the System Average Interruption Frequency Index (SAIFI), the System Average Interruption Duration Index (SAIDI), and voltage quality measures. These indices, in turn, provide robust metrics for evaluating the reliability and quality of electricity supply, thereby strengthening the empirical foundation for assessing the impact on MSMEs. Furthermore, unlike VoLL or CDF, which primarily reflect MSME willingness to pay, real-time reliability indicators such as SAIDI, SAIFI, and voltage metrics offer a more direct means of capturing the actual cost of unserved energy, quantify its financial impacts on utilities and also provide a consistent and objective basis for evaluating new network reinforcement (Ziari et al, 2012). Broadly, this enables utilities to align reliability planning with broader economic efficiency goals. Therefore, in the next section, we introduce nLine’s remote sensing tool, GridWatch to spatially, temporally and accurately capture PQR and its effects on MSMEs in an LIC - Sierra Leone. Our goal is to provide a stronger empirical foundation that captures the spatial and temporal dynamics of Freetown’s grid performance to enable targeted policy, investment, and utility reforms that improve electricity service delivery for MSMEs and the entire Freetown population.

3. Methodology

3.1 Country Context

As of 2021, Sierra Leone had an installed capacity of 238 MW (IRENA, 2022) with 61 MW from hydropower. A majority of this hydropower comes from the Bumbuna Hydroelectric Power Station, which produces 50 MW during the rainy season but drops to about 8 MW in the dry season (Khan and Koo, 2024). Domestic generation capacity—primarily hydropower—has not kept pace with rising demand, resulting in “frequent and persistent load shedding and rolling blackouts” in urban centers, including Freetown (Millennium Challenge Corporation, 2021). To fill the gap, Sierra Leone depends heavily on costly diesel generators and offshore power ships (Millennium Challenge Corporation, 2021; Khan and Koo, 2024).

The state-owned Electricity Generation and Transmission Company (EGTC) oversees generation and high-voltage transmission while the Electricity Distribution and Supply Authority (EDSA) manages the distribution network and customer sales. The country's single 161 kV transmission line connects Bumbuna to Freetown, where most electricity is consumed (Ministry of Energy, 2018; Millennium Challenge Corporation, 2021). Losses across the transmission and distribution network are substantial, approaching 40% in some areas (World Bank, 2016, as cited in Millennium Challenge Corporation, 2021). Further, seasonal variability in hydropower output, limited grid infrastructure, and weak institutional capacity constrain reliable supply (Khan and Koo, 2024). In an effort to help with the provision of reliable electricity supply to urban centers such as Freetown, the newly constructed Côte d'Ivoire-Liberia-Sierra Leone-Guinea electricity interconnection line (TRANSCO CLSG) began transmitting a peak of 50MW to the capital via EGTC's 161 kV transmission line in July 2022. As a result, EDSA now has three sources of power generation: Karpowership, Bumbuna, and TRANSCO (TRANSCO CLSG, 2022).

However, despite major electricity investments including the connection of Freetown to the CLSG grid, 24-hour electricity has fallen short of the expected output and Sierra Leone's constrained grid capacity continues to impede economic productivity and the country's vision of industrialisation. "Only about a fourth of the country's population has access to gridded power, most of which lives inside the capital Freetown" (Millennium Challenge Corporation, 2021). The consequences of inadequate and unreliable electricity are wide-reaching, especially for enterprises who depend on reliable power supply for operations. A recent World Bank survey found that 152 private firms in Sierra Leone lost, on average, 11.2% of annual revenue due to unreliable electricity—more than double the sub-Saharan African average of 5.3% (World Bank, 2020, as cited in Khan and Koo, 2024). These outages raise business operating costs, limit productivity, and deter investment, particularly in manufacturing and services.

Urbanization in Sierra Leone is increasing—averaging over 3% annually between 2010 and 2019—but this growth "masks the poor infrastructure and low private investment necessary to stimulate higher-value production and gainfully employ an ever-growing bulge of young workers" (Millennium Challenge Corporation, 2021). PQR in Sierra Leone is far from homogenous and is intertwined with economic, environmental, and social inequalities: 80% of those who experience chronic poor PQR in Sierra Leone live in urban and peri-urban spaces and operate MSMEs that deliver more than 50% of the country's job creation (World Bank, 2022). According to the World Bank's 2020 Doing Business Report—which assesses and compares the ease of doing business in various economies—Sierra Leone ranked 163rd out of 190 economies globally.

Systemic barriers—such as underinvestment in infrastructure, poor financial viability of utilities due to weak cost recovery, and planning and governance constraints—hinder the potential for businesses to operate at full capacity and the poverty-reducing potential of urban growth. Central to these barriers is a fundamental data gap: the absence of real-time, high-resolution monitoring systems that can capture the spatial and temporal dynamics of grid performance. We argue that without grid visibility, it is impossible to design, target, and implement effective interventions to improve electricity service delivery.

3.2 Site-Selection Strategy

For this study, we used maps to identify areas across Western Urban and Western Rural districts in Freetown with a high concentration of grid-connected MSMEs. Our sampling strategy was purposive and aimed at obtaining high coverage of voltage and power outage KPIs along the length of the distribution infrastructure in urban and peri-urban Freetown. While grid network maps were unobtainable from EDSA, we leveraged gridfinder (https://github.com/carderne/gridfinder)—an open source tool for predicting the location of electricity network lines—to estimate HV and MV networks across Freetown.

Figure 1: A map of the estimated transmission network location across Freetown (source: gridfinder).

We wanted to ensure that we had a geographically dispersed sample of MSMEs to evaluate major variations in PQR within the EDSA grid network across Freetown. We identified 12 communities (shown in Figure 2) with a high concentration of grid-connected MSMEs as areas for GridWatch sensor installations.

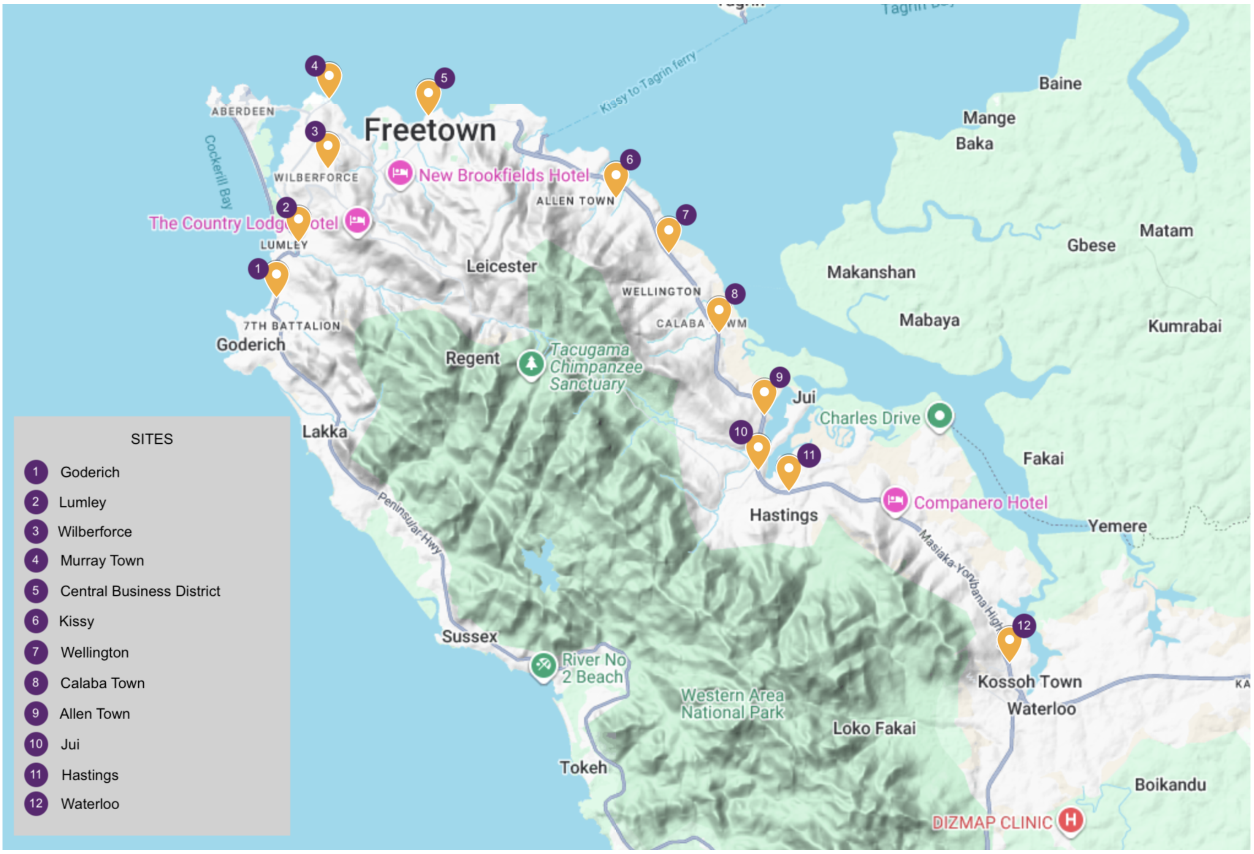

Figure 2: Twelve communities ("sites") with a high concentration of MSMEs that were selected for GridWatch sensor installation. These sites are spread along Freetown's HV and MV grid network.

Once these 12 communities or "sites" were identified, our in-country Project Manager visited each of these sites to identify a single low-voltage distribution transformer that would anchor the businesses where we would install GridWatch sensors. A distribution transformer was selected if at least 15 MSMEs appeared to be visually connected to the transformer; this allowed for ample flexibility in identifying four eligible MSMEs under each transformer for GridWatch sensor installation (see the section "GridWatch Sensor Installation" for details on MSME eligibility). The GPS locations of each of the 12 transformers were recorded so *n*Line's team of enumerators could re-visit the sites for surveying and GridWatch sensor installation.

3.3 Data-Collection Approach

3.3.1 GridWatch Sensor

GridWatch sensors measure the voltage magnitude, AC frequency, power outages, and power restorations time-stamped to the millisecond, and the GPS-based location of the power outlet. Integrated global SIM cards capture data at two-minute intervals over the cellular network and a battery enables continuous data reporting throughout a power outage. If there are GSM network connectivity problems, data is queued and uploaded once connectivity is restored. To detect power outages and evaluate their extent, we identify simultaneous reports of individual sensors losing power close in space and time and perform additional analysis. Finally, data are aggregated to produce PQR KPIs for each “site” (see the section “Key Performance Indicators” for further details).

Figure 3: A GridWatch sensor plugged into a wall outlet at a grid-connected business in Freetown.

3.3.1.1 GridWatch Sensor Installation

A single “site” consists of four GridWatch sensors deployed at wall outlets in four separate MSMEs on a common feeder—i.e., under the same medium voltage (MV) to low voltage (LV) transformer. Beginning at the GPS location of the pre-selected distribution transformer, *n*Line’s field team of enumerators visually traced the overhead lines originating from the transformer to locate MSMEs that are connected to the transformer and would serve as potential businesses to approach for surveying and sensor installation. To ensure the accuracy of our approach, we also used existing physical infrastructure maps during deployment to ensure sensors were placed to capture the state of the network with maximal fidelity and best estimate performance of the bulk grid.

Installing sensors with four MSMEs connected to the same LV transformer allows *n*Line to cluster outage reports from several sensors that are connected to the same distribution transformer, understand how electricity impacts individual businesses, compute business-level PQR measurements and while also generating grid-level insights. By clustering, we are also able to filter out "false" outage reports caused by customer behaviour or sensor issues (e.g., a customer may have run out of prepaid credit, unplugged the sensor, or intentionally switched off their main power supply) to ensure accurate detection and quantification of power quality (for further details, please refer to *n*Line's blog "A Clustering Algorithm for Power Outage Detection").

*n*Line's in-country Project Manager and staff led a three-day training in Freetown with enumerators to ensure correct protocols were used when obtaining informed consent from business owners, when conducting surveys and interviews, and when plugging in GridWatch sensors. Beginning on November 1 through November 3, 2024, 48 sensors were deployed with 48 MSMEs across the 12 sites.

From the GPS location of the pre-selected distribution transformer in each site, four enumerators walked in all four cardinal directions (if possible) from the transformer to begin to approach businesses. Enumerators approached a business if it met the following visual eligibility criteria:

1. By visually tracing the power line from the distribution transformer, it appears the business is connected to the pre-selected transformer.
2. The business has a solid roof, four solid walls, and can be securely shut in the evenings (*to ensure the sensor is less likely to be stolen or damaged by rain*).

If a business passed the visual criteria, the enumerator would approach the business for surveying to determine eligibility for GridWatch sensor installation based on the following criteria:

1. The business owner is physically present at the shop during the time of surveying and consents to sensor installation.
2. The business owner intends for this business to remain at the same location for at least the next 6 months (*to ensure longitudinal data will be collected for at least six months)*.
3. The business is supplied with EDSA power.
4. There is no solar providing power to the wall outlets at the business (*to ensure sensors are generating PQR KPIs for EDSA grid power only*).
5. There is no generator providing power to the wall outlets at the business (*to ensure sensors are generating PQR KPIs for EDSA grid power only*).
6. There are at least two functioning wall outlets at the business (*to ensure that the sensor will not occupy the only available wall outlet and thus likely be unplugged for the use of appliances and equipment*).

Figure 4: GridWatch sensors installed at outlets in small businesses in Goderich (left) and the Central Business District (right).

3.3.1.2 GridWatch-Measured Key Performance Indicators

nLine transforms raw sensor measurements into standardised and internationally recognised power system Key Performance Indicators (KPIs) such as SAIFI, SAIDI, and voltage quality metrics — widely adopted for benchmarking grid performance. We further disaggregate these KPIs, across multiple temporal resolutions (weekly, monthly, quarterly, annual) and spatial levels (feeders, transformers, service territories), as this enables rigorous auditing of PQR in medium-to- low-voltage networks. This approach enables us to conduct comparative performance and trend analysis across geographies and time, and quickly identify, detect and quantify systemic issues that may impact grid health and MSME service quality.

Table 1: Summary of KPIs measured by GridWatch.

KPI	Definition [units]
System Average Interruption Duration Index (SAIDI)	Average cumulative outage time experienced by a customer [hours]
System Average Interruption Frequency Index (SAIFI)	Average number of outages experienced by a customer [number of interruptions]
Customer Average Interruption Duration Index (CAIDI)	Average duration of any single outage experienced by a customer [hours]
Average Voltage	Average voltage delivered to customer [Vrms]
Hours Undervoltage	Average time customer experiences very low voltage [hours]
Minutes Overvoltage	Average time customer experiences very high voltage [minutes]

To assess PQR supplied to the 48 MSMEs, data were gathered from GridWatch sensors, in-person surveys, and ongoing qualitative engagements with business owners. The following two sections detail the in-person survey and ongoing field insights with MSMEs during the study period.

3.3.2 Surveys

*n*Line uses a survey to support the installation of the GridWatch sensors. This survey—administered in SurveyCTO—records a unique code for each installed sensor and a unique, randomly generated respondent ID for each sensor installation to assist with backend analysis and sensor tracking.

To help assess the impact of PQR on businesses' productivity, operating costs, and resilience strategies, the survey accompanying the initial sensor installation in November 2024 included questions related to participant business operations and experiences with electricity reliability (e.g., "what industry best describes this business?" and "how satisfied are you with the electricity from EDSA?"). MSME participants rated the quality of their electricity on a five-point likert scale ranging from 1 (very satisfied) to 5 (very dissatisfied), while the rest of the questions were grouped into yes/no nominal scales. For a complete list of MSME-related survey questions, see Table 1 in the Appendix.

3.3.2.1 Survey Data Analysis

Due to the small size (n=12) of our distribution transformer sample, we primarily focused on generating descriptive statistics and presenting bivariate correlations between poor experiences with PQR and business resilience strategies, and we treat findings from the survey as an opportunity sample.

3.3.3 Ongoing Qualitative Field Insights

Each day, the in-country Project Manager logged into *n*Line's backend sensor-monitoring system to check the performance of installed sensors. If a particular sensor's data revealed irregularities in power reliability and/or quality at any point during the data-collection period, the Project Manager contacted the business owner to inquire about the issue. By reaching out directly to the business owner via Whatsapp and/or in-person visits, qualitative field insights were able to complement sensor measurements to better understand socio-economic or techno-economic factors that may be impacting PQR. For example, through discussions with business owners we learned that some causes of sensor-detected power outages included: (1) lack of funds to pay for EDSA grid power; (2) voltage surges that damaged the outlet where the sensor was installed; and (3) business owners temporarily shutting off power and closing shop due to illnesses or family emergencies. This type of qualitative field insight helps distinguish between true PQR issues and issues that impact PQR but are derived from outside of the energy system itself.

4. Findings

In this section, we present empirical findings on the nature, scale, and spatial variation of PQR issues affecting sampled MSMEs and distribution infrastructure across Freetown. In 4.1 we provide descriptive analysis of survey responses from MSMEs participants. Specifically, we highlight insights around four variables: industry type, experiences with outages and voltage quality, cost of outages on business productivity, and business resilience strategies. In 4.2 we dive into the GridWatch data to characterise grid-wide patterns of outages and map the nature and distribution of PQR challenges across monitored sites. In 4.3 we examine the impact of voltage quality on MSMEs, combining sensor measurements with qualitative field insights to assess effects on the functionality, performance, and longevity of appliances. In 4.4 we provide a preliminary estimate of the economic cost of outages to the national utility (EDSA) to inform planning, operational prioritization, and investment decisions.

4.1 Survey findings

This section summarises survey results from 48 MSMEs with GridWatch sensors installed across 12 communities in Freetown. In the following subsections, we present detailed findings on participant composition, participants' perceptions of EDSA's power quality and its impact on daily operations, and overall productivity and coping strategies adopted by businesses.

4.1.1 Participant Composition and Appliance Ownership

To understand the spatial nature of PQR across Freetown, our sample of MSMEs are spatially distributed across the eastern [Calaba Town, Jui Kissy, Waterloo, Wellington, and Hastings] and western parts of Freetown [Central Business District, Goderich, Lumley, Murray Town, and Wilberforce]. As shown in Figure 5, 56% of MSME shop owners sampled were male while 44% were female. In Figure 6, 62% of the sampled participants identified as small shop owners, 23% identified as medium sized/commercial enterprises, and 15% identified as "other".

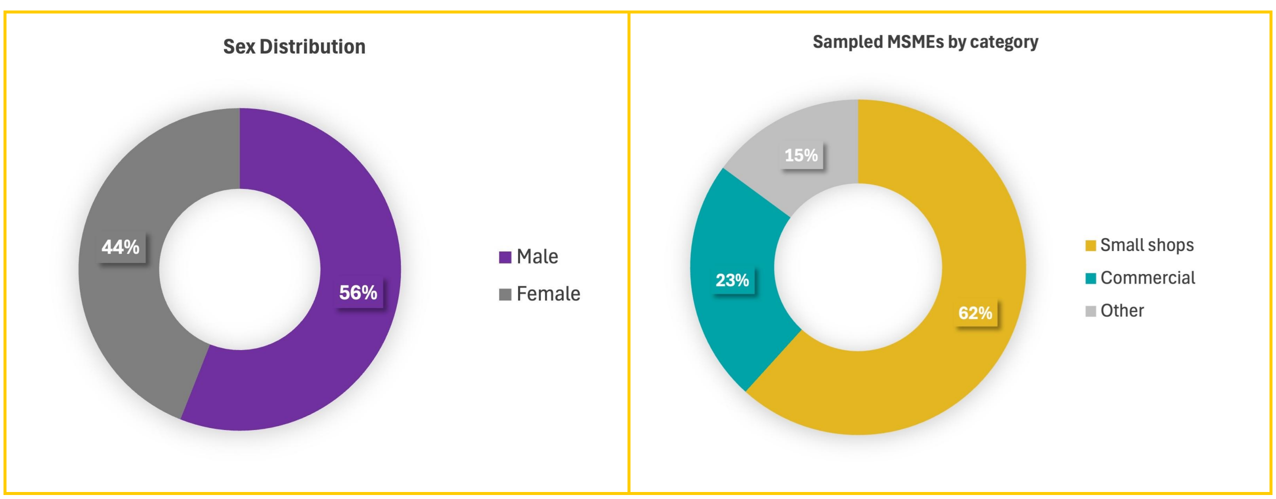

Figure 5 and **Figure 6:** Distribution of MSME survey participants by sex and industry category, respectively.

Appliance ownership varied based on business type and electricity intensity/usage of the business. As shown in Table 2, a considerable proportion of surveyed MSMEs reported ownership of energy-intensive appliances like electric sewing machines, air conditioners, and laundry machines. A large share also owned freezers and water heaters. Other commonly reported, though less energy-demanding, appliances include fans, printing equipment, computers, and ice-cream machines.

Table 2: Appliance ownership by MSMEs across monitored sites/communities

Community	Types of businesses	Appliance ownership
Allen Town	Groceries, packaged foods and drinks	Five freezers, one water heater, one desktop computer, two fans, one plasma TV, and one AC
Calaba Town	Electronic items, electronic services	Five freezers, three fans, one water heater, and one plasma TV
Central Business District	Groceries, packaged foods and drinks	Two freezers, one popcorn machine, one ice cream machine, and one water heater
Goderich	Electronic items, electronic services, groceries, printing shop	Nine freezers, four printers, four computers, eight fans, one laminating machine, water heater, four ACs, two fridges, one microwave, one toaster, and one electric kettle
Hastings	Tailoring, groceries, packaged foods and drinks	Two freezers, two fans, and one plasma TV
Jui	Tailoring, hair salon, groceries, packaged foods and drinks	Two freezers, one water heater, five fans, and two plasma TVs
Kissy	Groceries, packaged foods and drinks	Nine freezers, two fans, one ice cream machine, one microwave, one rice cooker, one toaster, one popcorn machine, and one egg boiler
Lumley	Tailoring, hair salon, groceries, restaurant	One freezer, four fans, one TV, one AC and one fridge
Murray Town	Electronic services, medical supplies and groceries	Four freezers, one water heater, three fans, and two TVs
Waterloo	Medical supplies, groceries	Five freezers, two fridges, and four fans
Wellington	Tailoring, hair salon, groceries, plumbing	Three freezers, five fans, one water heater, one electric goose, one plasma TV, one home theatre set, and two electric sewing machines
Wilberforce	Tailoring, groceries	Six freezers, three water heaters, two electric kettles, two fans, three laundry machines, and one dryer

4.1.2 Participant Satisfaction with EDSA Power, Reported Electricity Reliability, and Costs

The data reveals significant variation in participants' satisfaction levels with EDSA power, with Waterloo showing the highest dissatisfaction (all four MSMEs rated "Very Dissatisfied"), while other communities display more mixed patterns. Unsurprisingly, MSMEs in the CBD area and Wilberforce - areas known for its concentration of Sierra Leone's legal, business, and diplomatic communities reported more satisfaction than elsewhere. However, none of the MSMEs were "very satisfied" with EDSA.

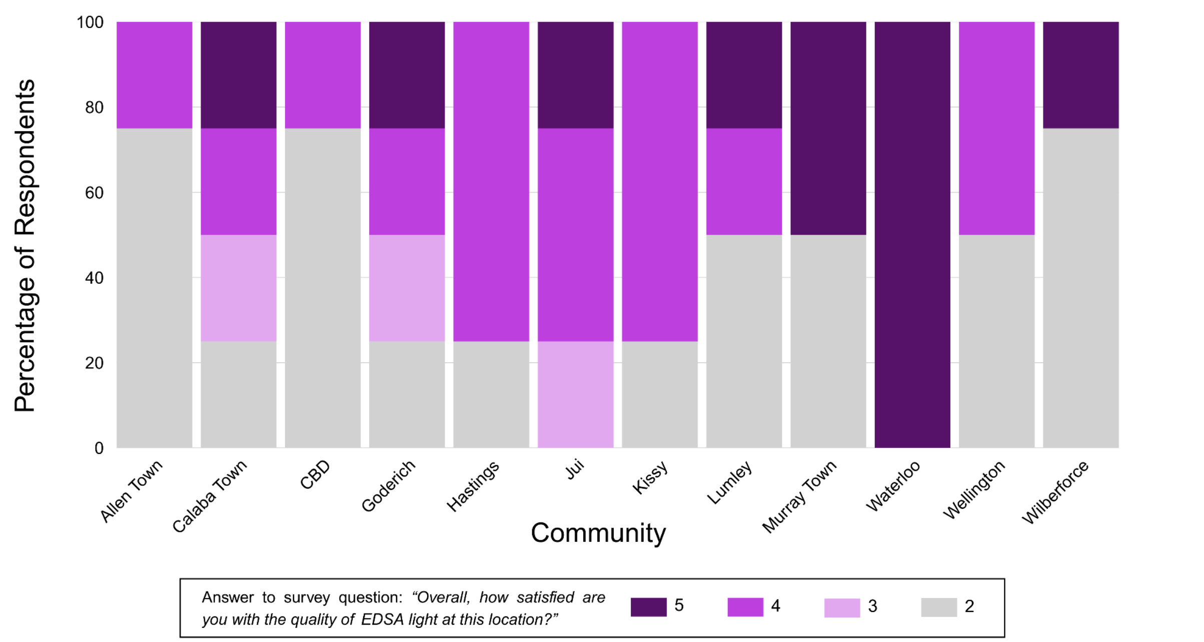

Figure 7: Distribution of grid power satisfaction ratings by community. In each community, four MSMEs were asked to rank satisfaction with EDSA power quality. Ratings range from 1 (Very Satisfied) to 5 (Very Dissatisfied).

In response to the survey question "In the last week (last 7 days), how many EDSA outages did you experience at this location?" 41.7% of MSME participants reported experiencing an average of 2-5 outage interruptions per week, 29.2% reported 6-10 outages, 20.8% reported 11-20 outages, and 8.3% reported more than 20 outages in a week. As seen in Figure 8, there is significant variation in MSME self-reported frequency of outage interruptions within and across communities.

Participants were also asked to self-report on the duration of each outage experienced in the previous week ("For how long does each of these EDSA power outages usually last?"). By multiplying this duration with the reported number of power outages, we estimated the average total number of hours without power in a week for a MSME. As seen in Figure 9, 25% of MSME participants reported an average of 0-10 hours of outages per week, 14.6% reported experiencing about 11-20 hours of outages per week, and 60.4% reported more than 20 hours of outages per week. MSMES in Waterloo, Jui, and Hastings reported higher durations compared to other communities. Self-reported SAIDI and SAIFI highlight the diverse experiences of reliability among MSMEs in Freetown.

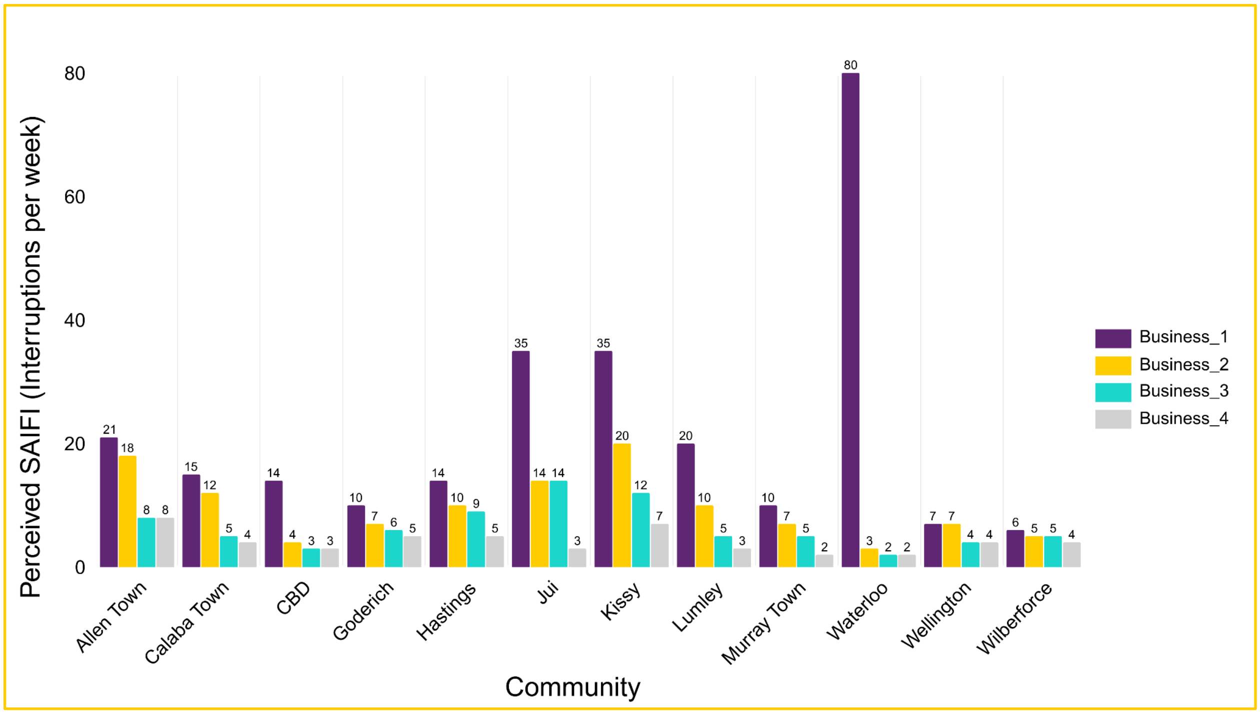

Figure 8: Weekly MSME-reported SAIFI across 12 communities. Each bar represents an individual business response, showing substantial variation both within communities (e.g., in Waterloo where three MSMEs reported experiencing 2-3 outages/week and one MSME reported experiencing 80 outages) and between different communities (e.g., comparing Wilberforce, with an average of 5 self-reported outages/week, and Kissy, with an average of 18.5).

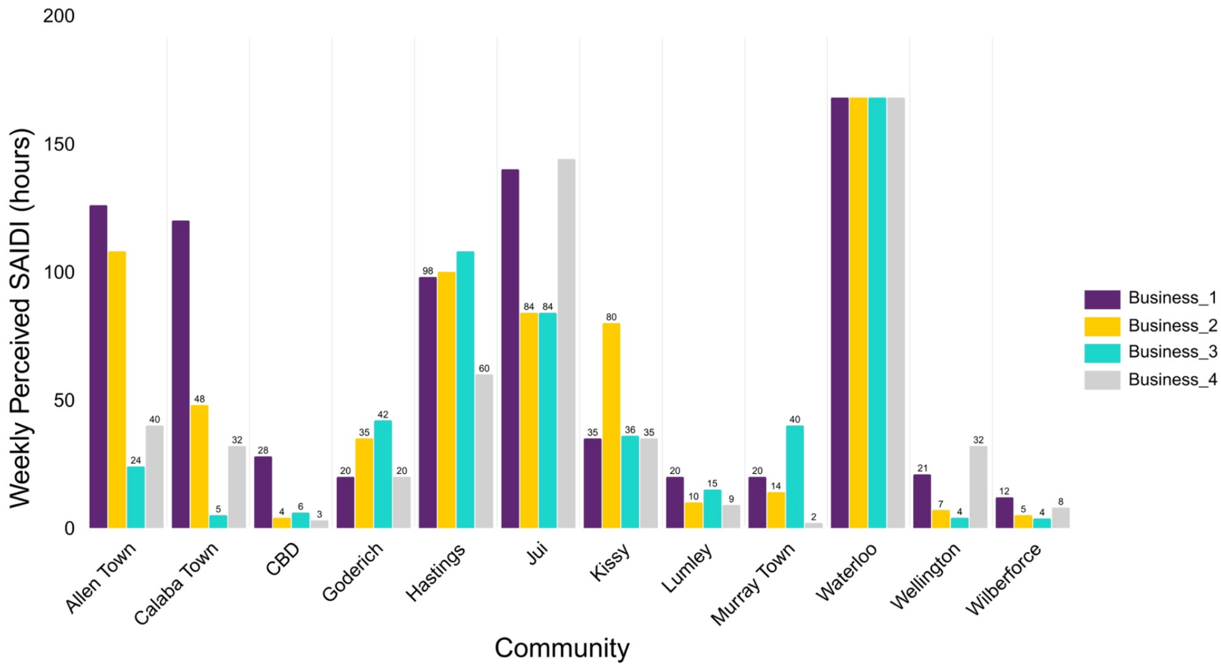

Figure 9: Weekly MSME-reported SAIDI across 12 communities. Each bar represents an individual business response, showing substantial variation both within communities (e.g., in Calaba Town, where one MSME reported experience 5 hours of total outage and one reported experiencing 125 hours) and between different communities (e.g., comparing Waterloo, where all four MSMEs reported experiencing outages spanning an entire week, with Wilberforce, where all four MSMEs reported outage totals of 12 or fewer hours).

Electricity expenditure patterns among MSMEs can serve as indirect yet informative indicators of several critical dimensions of business operations. Specifically, monthly or weekly electricity costs may reflect: (i) the reliability of electricity supply experienced by these enterprises; (ii) their recognition or treatment as "special" or priority customers within the electricity distribution framework; and (iii) the intensity of their operations, including their capacity to absorb outage-related shocks and their broader resilience strategies.

To examine the perceived scale of electricity reliability among MSMEs in our study and assess whether this correlates with electricity cost, we categorised MSME participants into three electricity expenditure groups: Group 1 (0–99 NLe spent weekly on EDSA electricity), Group 2 (100–499 NLe spent weekly on EDSA electricity), and Group 3 (500–999 NLe spent weekly on EDSA electricity). The distribution of enterprises across these categories highlights noteworthy differences in both energy intensity, experience, and likely scale of business operations. As illustrated in Figure 10, MSMEs in the highest spending group (500–999 NLe per week) reported comparatively fewer outages and yet expressed less satisfaction with EDSA's services.

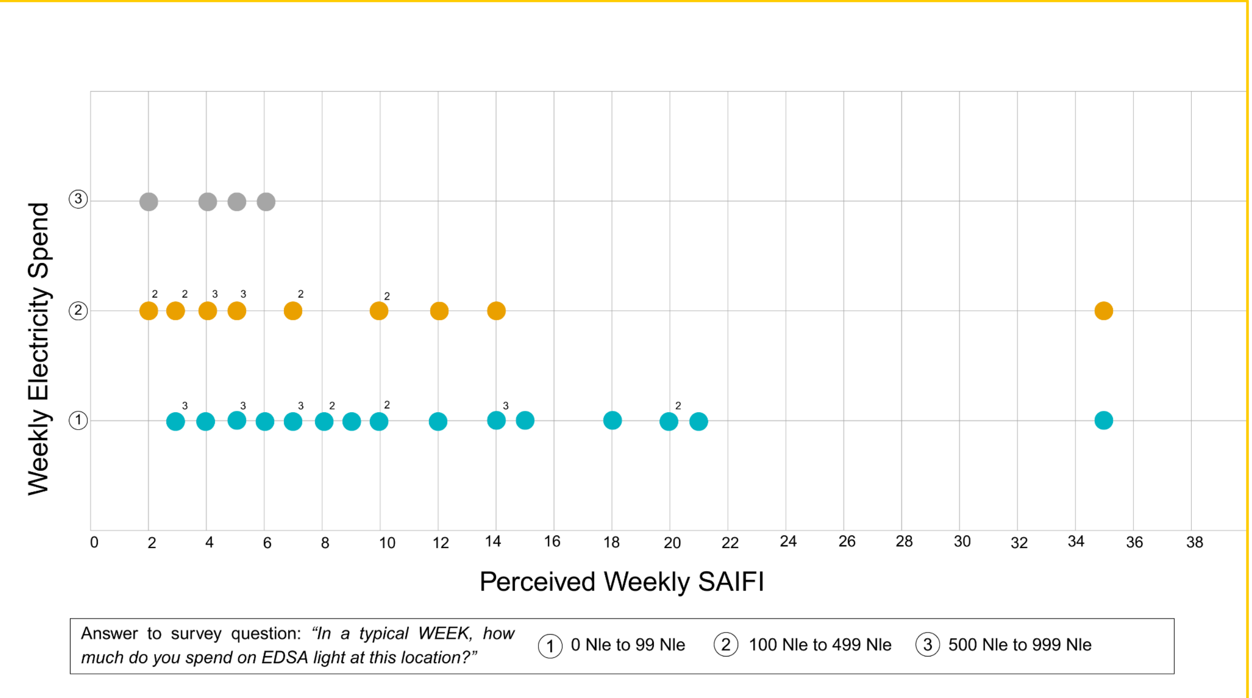

Figure 10: Weekly self-reported experiences of outages vs. amount spent on electricity. Customer-reported power interruption frequency across three electricity spending categories (0-99 Nle, 100-499 Nle, 500-999 Nle).

In contrast, MSMEs in the 100–499 NLe weekly expenditure category reported outage frequencies only about 30% lower than those of the lowest-spending group (0–99 NLe weekly), indicating that moderate increases in electricity expenditure did not necessarily translate into proportional improvements in reliability. Also, the reported higher electricity cost shares of MSMEs in the 500–999 NLe weekly group suggest that these businesses likely operate with greater energy intensity and are more likely vulnerable to electricity disruptions.

4.1.3 Participant-Reported Impact of Power Quality on MSME Operations

It is widely documented that poor power quality disrupts business operations, as outages or voltage fluctuations can cause loss of trade, translate into idle labour and machinery, or even cause equipment damage. As seen in Figure 11, 70.8% of MSME participants reported that poor power quality had led to appliance damage. Some businesses that reported high outage frequency (e.g., 35 outages/week in Jui and Kissy) reported no equipment damage, whereas others which reported far fewer outages (e.g., 3 outages in Waterloo) did report appliance damage. This seeming paradox actually suggests problems with voltage quality rather than outage frequency, because severe voltage fluctuations—such as spikes and sags during "load shedding"—can be more harmful to appliances than the outage event itself.

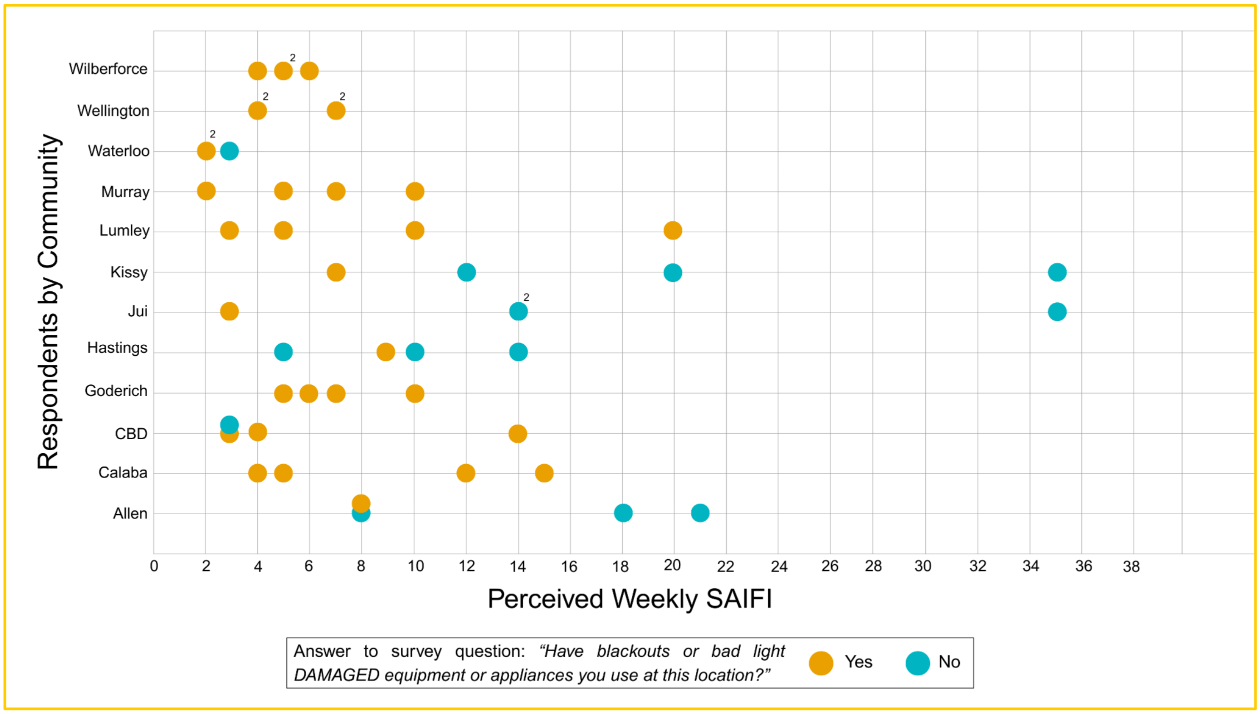

Figure 11: Perceived weekly SAIFI and equipment damage by community. The data reveals that equipment damage is widespread across all perceived SAIFI levels, with a majority of respondents (34 out of 48, or 70.8%) reporting that "bad light" has damaged their equipment or appliances.

These findings highlight that voltage quality matters as much as outages. It also suggests variations in equipment sensitivity, protective measures, operational practices, and grid conditions experienced by MSMEs. It is likely that MSMEs that avoided damage despite frequent outages may have adapted (i.e., taken resilience measures to reduce damage risk) by performing immediate appliance shutdowns during outage events or utilised protective devices like UPS units or voltage stabilizers that cushion appliances from voltage shocks. MSMEs which reportedly suffered damage despite fewer outages may lack protective devices or rely on aging or sensitive machinery with low tolerance to voltage spikes or sags.

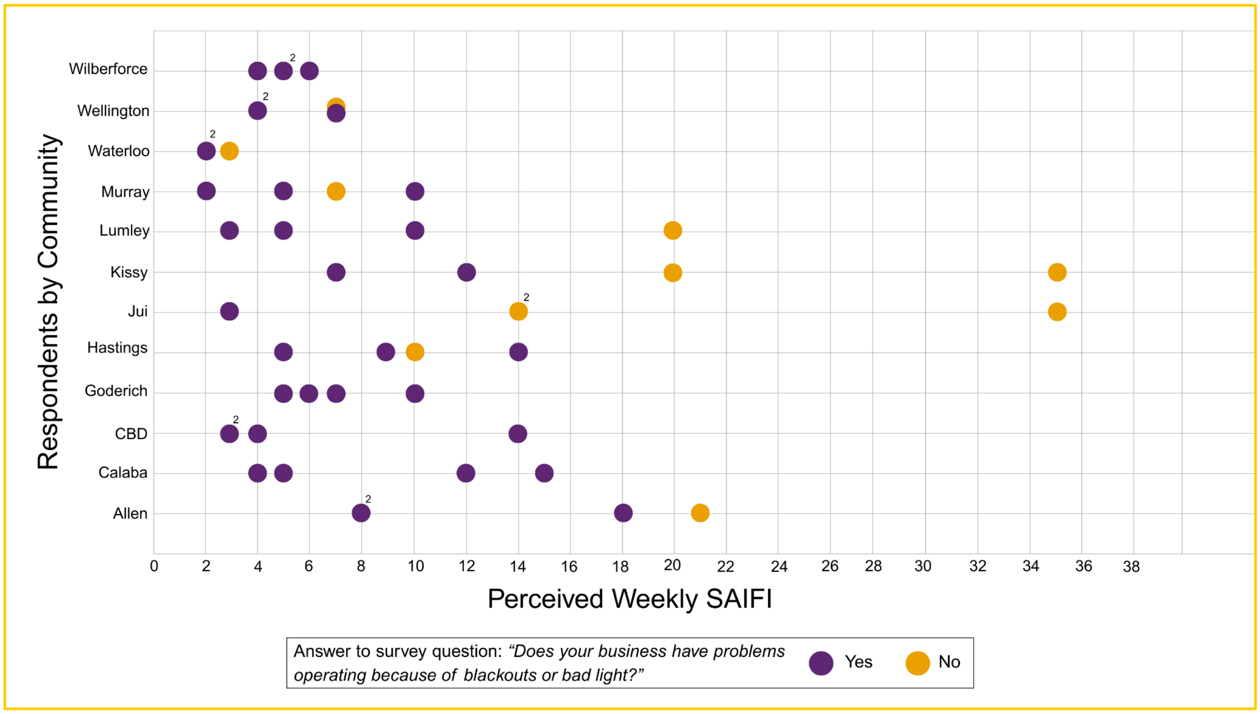

Figure 12: Perceived weekly MSME experiences of outages vs. operational impact by community. Individual business responses showing perceived weekly SAIFI across 12 communities. 75.% of respondents reported experiencing operational disruptions from outages.

Beyond appliance damage, a more fundamental concern relates to the broader impact of power outages on MSME operations and their spillover effects on productivity. As illustrated in Figure 12, 75% of MSMEs reported experiencing operational disruptions attributable to outages. Surprisingly, MSMEs that reported higher frequency of outages indicated fewer operational disruptions. This finding is both conceptually and empirically interesting; a plausible explanation for this asymmetry may be the presence of adaptive coping mechanisms or resilience strategies among these MSME.

4.2 GridWatch Findings

4.2.1 System Reliability Across Monitored Segments of the Grid

We start by providing a summary of the average daily values of reliability experienced by MSMEs across all 12 monitored communities. We consider reliability in terms of two metrics: SAIDI and SAIFI (see methodology for definitions), which respectively capture the cumulative duration and number of outages experienced on average within each community. The GridWatch data shows significant variability in the average number, frequency, and duration of outages experienced by EDSA MSME customers. For example, the four sampled MSMEs in the Central Business District (CBD) area experienced the shortest outages on any given day, with only 1.48 hours of cumulative outage time and 0.83 hours per individual outage event. In contrast, sampled MSMEs in Hastings experienced on average 13.3 hours of outage time per day spread over 2.12 outage events. Thus, each outage event in Hastings lasted about 6.27 hours, over 7.5 times longer than those in the CBD. Outages of this scale and duration render appliances idle, reduce production hours, and may ultimately force MSMEs to outsource part of their production or services or switch to less-electricity-intensive methods to remain in business.

Table 3: Average Daily Power Reliability KPI Values for the 3 Best-Performing and 3 Worst-Performing Sites. For KPI values for all sites, see Table 1 in the Appendix.

KPI	Definition	Unit	Site	KPI Value
Daily SAIDI	Average cumulative outage time experienced by a customer	Hours per day	Central Business District	1.48
			Lumley	2.37
			Murray Town	2.75
			Allen Town	10.4
			Waterloo	11.9
			Hastings	13.3
Daily SAIFI	Average number of outages experienced by a customer	Number of interruptions per day	Murray Town	1.18
			Goderich	1.67

			Wellington	1.69
			Hastings	2.12
			Allen Town	2.15
			Kissy	2.19
Daily CAIDI	Average duration of any single outage experienced by a customer	Hours per day	Central Business District	0.83
			Lumley	1.20
			Wilberforce	1.53
			Jui	5.31
			Waterloo	5.95
			Hastings	6.27

4.2.1.1 Distinct Grid Segmentation Is Observed Through Large Outage Patterns

An event is flagged as a grid outage when at least two installed sensors lose power at approximately the same time and are located within a defined spatial threshold. The threshold is applied contiguously: sensors are grouped into clusters if each sensor is within the distance threshold of at least one other sensor in the group. In this way, clusters can expand outward during widespread outages as long as each new sensor is close enough to at least one other sensor already in the cluster. For each detected outage, we record both the number of affected businesses and the number of transformers affected. We define an outage as “large” if it affects more than two monitored distribution transformers.

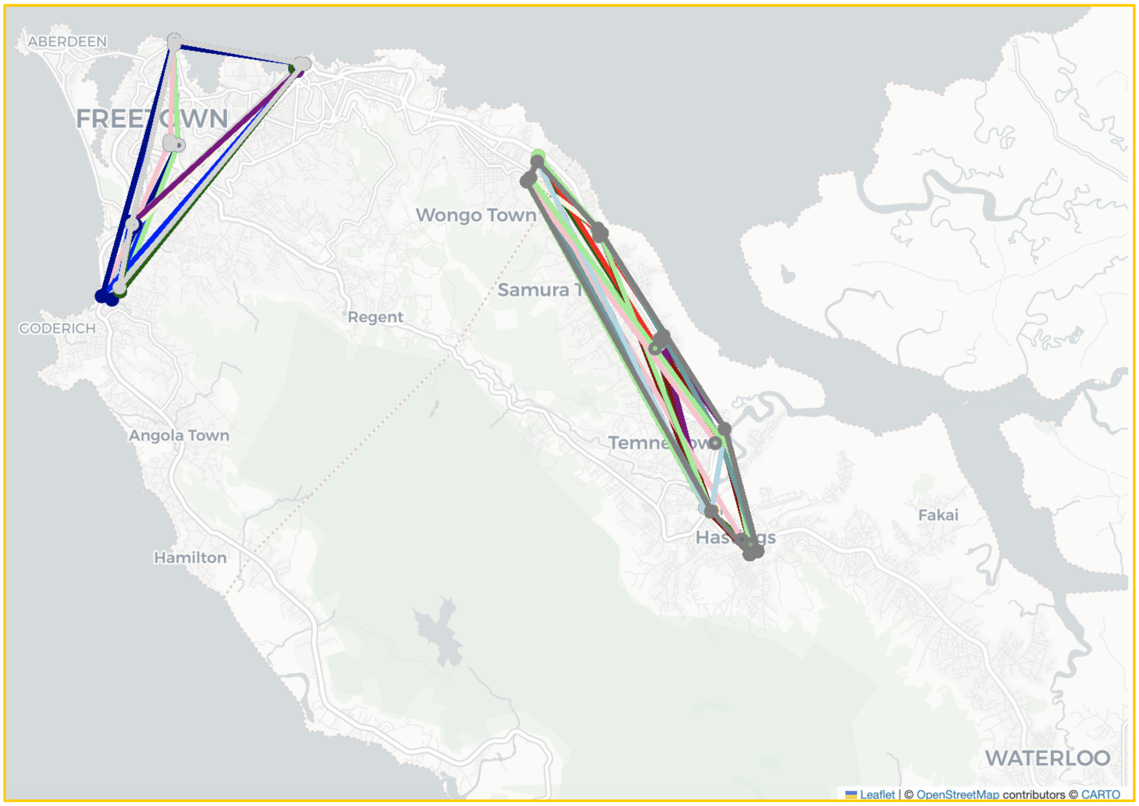

Figure 13: Power outage clusters for large outages (November 2024 through July 2025). Each individual polygon represents a large outage event, and its vertices are the locations of the sites involved in the event. Large outages measured by GridWatch sensors affect the MSMEs in two distinct groups: the Western area and the Eastern area of Freetown.

We observed frequent large outages across the 12 monitored communities. Our analysis of these large outages shows that they were never random: each time a large outage occurred, it simultaneously affected one of the same two sets of communities—one group of five sites in the Western side of Freetown (Goderich, Lumley, Wilberforce, the CBD, and Murray Town) and another group of six sites in the Eastern side (Hastings, Jui, Allen Town, Calaba Town, Wellington, and Kissy). The outage clusters are shown on the map in Figure 13, and the voltage time series graph showing simultaneous outage reports across all transformers in a group (West or East) are shown in Figures 14 and 15. This repeated pattern indicates that the communities within each group share common grid infrastructure.

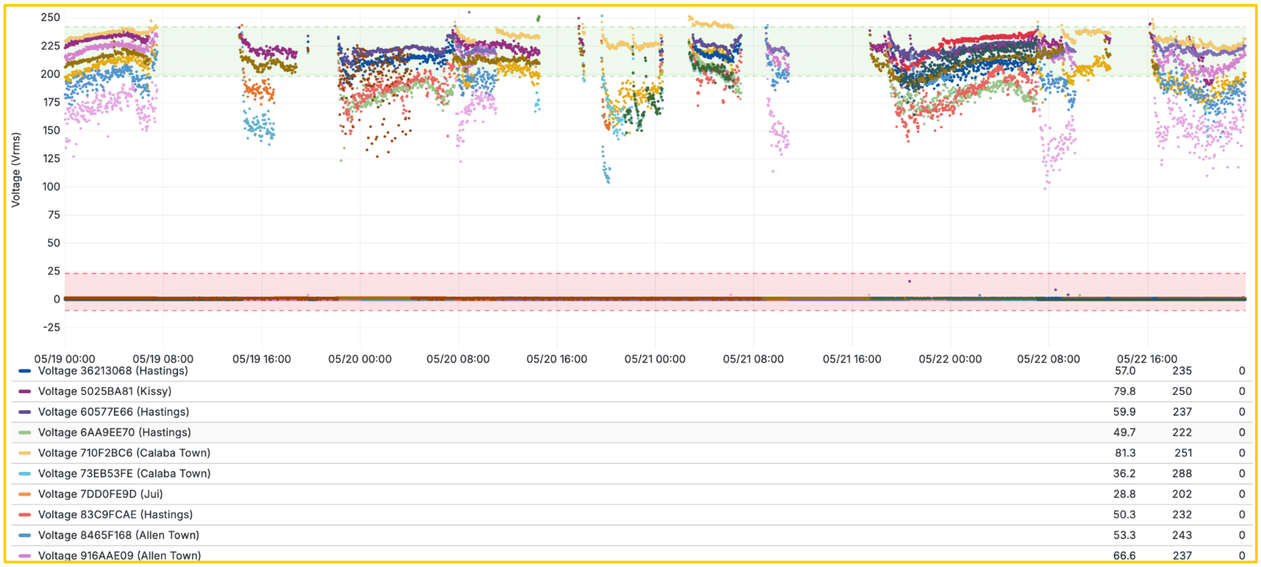

Figure 14: Frequent large outages affecting the sites in the Eastern area of Freetown from May 19 to May 22, 2025. The sites in the Eastern area are: Kissy, Wellington, Calaba Town, Allen Town, Jui, and Hastings. In this graph, outage events are the blank spaces where voltage data is not reported.

Figure 15: Frequent large outages affecting the sites in the Western area of Freetown from May 19 to May 22, 2025. The sites in the Western area are: CBD, Murray Town, Wilberforce, Lumley, and Goderich. In this graph, outage events are the blank spaces where voltage data is not reported.

Data from EDSA on substation locations reinforces this interpretation. In the Western area, where all monitored distribution transformers consistently go out simultaneously in large outages, EDSA data indicate that the transformers are supplied by at least three different substations (Wilberforce, Lumley, and Goderich substations). This suggests that the substations are failing together. The origin of these outage events is therefore most likely at a higher level of the grid—either a high-voltage (HV) transmission line feeding the substations or the Bulk Supply Point (BSP) upstream of them.

The same pattern is observed in the Eastern area, where multiple substations supplying the monitored communities (Raportee, Blackhall Road, and Wellington substations) also go out concurrently, again pointing to transmission- or BSP-level vulnerabilities. These outage patterns indicate that the MSME clusters within each group are likely served by a common HV transmission line or BSP, whereas Waterloo, which is outside Freetown, may be supplied via a separate line or network segment.

4.2.1.2 The Scale and Duration of Outages Vary Between Western and Eastern Sites

We also observed differences in duration and predominant scale of outages between the MSMEs in the East and the West. MSMEs in the East predominantly experienced large HV outages, whereas those in the West—closer to the CBD—mostly faced smaller, low voltage (LV) outages.

Figure 16 shows the distribution of outage types across the 12 monitored communities. The percentages are calculated by classifying each detected outage event into either a "small localized outage" (affecting ≤2 monitored communities/transformers) or a "large outage" (affecting >2 monitored communities/transformers).

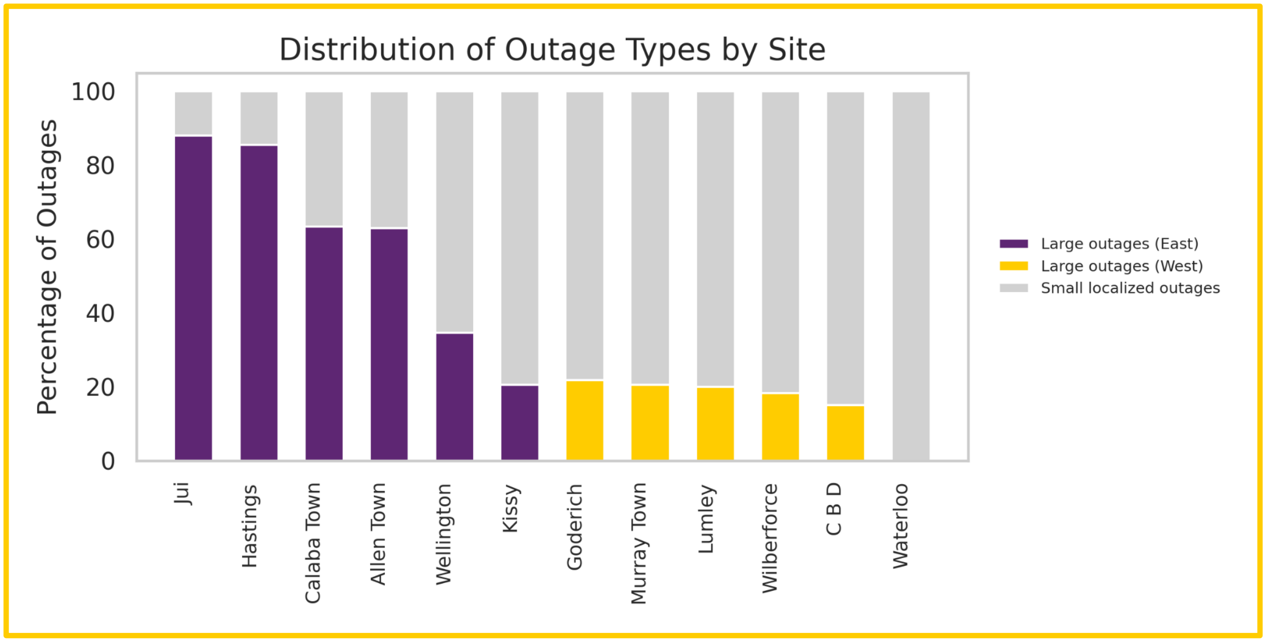

Figure 16: MSMEs in the Eastern area predominantly experienced large outages while those in the Western area mostly experienced smaller, localized outages. Waterloo, which is outside the East or West areas of Freetown, *only* experienced small outages, which could be as a result of not having other sensors deployed nearby (it is geographically the furthest from other sites).

In Jui, for instance, more than 80% of recorded outages were large events affecting multiple communities simultaneously. This indicates that most outages in Jui originate at the HV level (e.g., transmission line or upstream BSP) rather than at the local LV distribution level. In contrast, sites such as CBD and Wilberforce experienced predominantly small localized outages, suggesting more frequent LV-level disruptions. All Waterloo outages were at the LV level, which may suggest resilient upstream infrastructure or, more likely, its distance from other monitored transformers, which prevents outages from being clustered together under our analysis method.

SAIDI durations also differ notably between MSMEs in the East and those in the West. MSMEs in the East experienced prolonged outages, with SAIDI frequently surpassing 600 hours per quarter, while quarterly SAIDI in the West generally remained under 400 hours. Notably, sites with the shortest quarterly SAIDI in the East (e.g., Wellington and Kissy) often have similar outage durations to sites with the worst SAIDI in the West (e.g., Goderich)—as shown in Figures 17 and 18. The duration of these outages is consequential for MSMEs, directly impacting their capacity to meet daily operational targets and deliver services on schedule, resulting in reduced output and productivity.

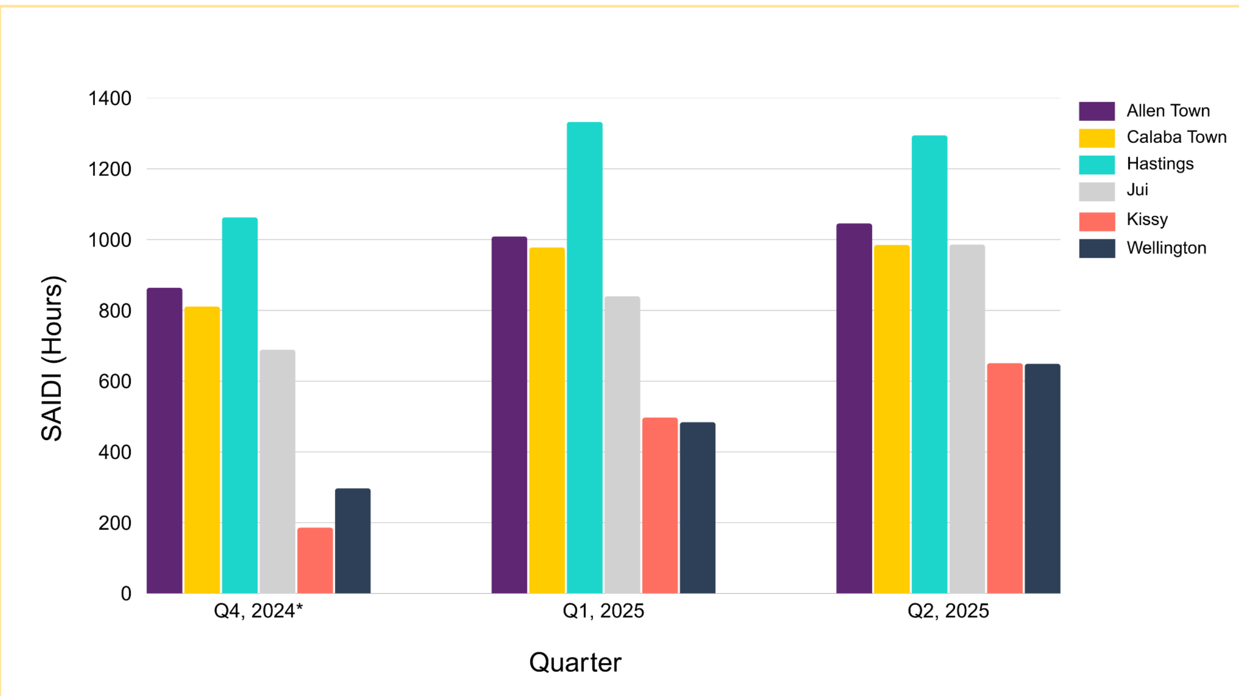

Figure 17: Quarterly[1] SAIDI in the Eastern sites. For most of these sites, and in most quarters, SAIDI exceeds 600 hours. MSMEs in Hastings consistently suffer the longest outage durations.

[1] Q4, 2024 contains data for only two months (November and December) as data collection began in November 2024.

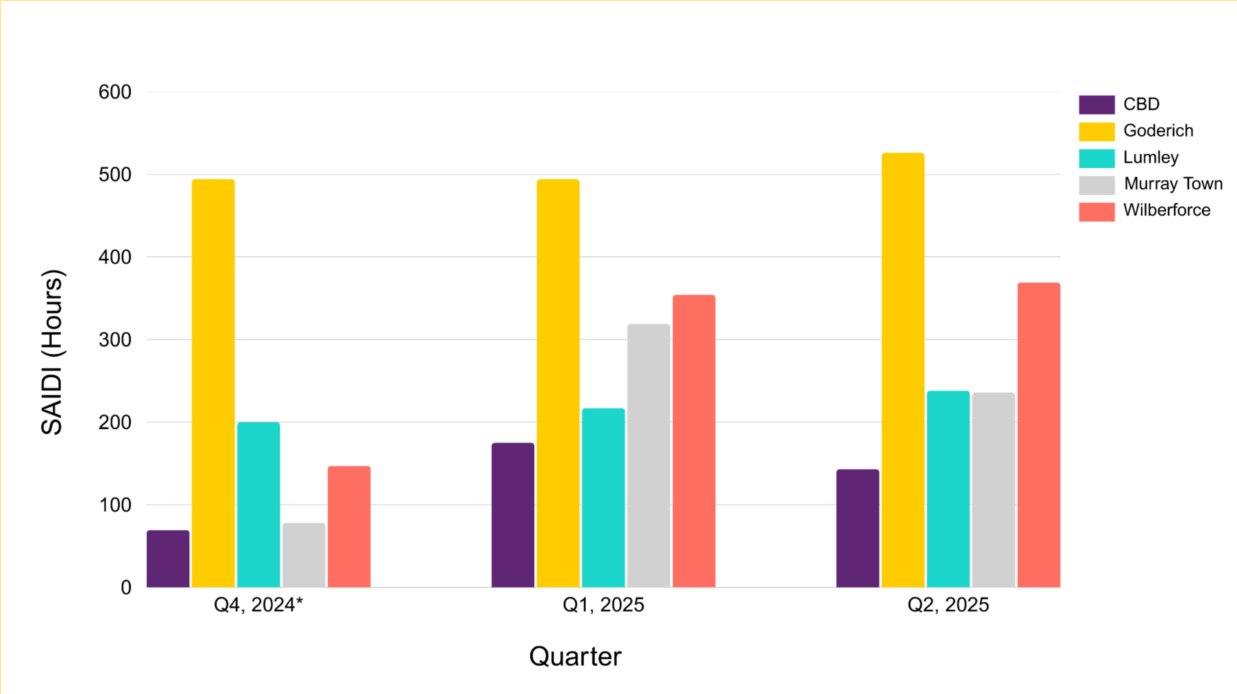

Figure 18: Quarterly[2] SAIDI in the Western sites. For most of these sites, and in most quarters, SAIDI stays below 400 hours. MSMEs in CBD, Lumley, and Murray Town typically experience the shortest outages.

The prevalence of large and longer HV outages in the East suggests systemic vulnerabilities at the transmission line or BSP level. Several factors may be contributing to these outages:

(i) feeder overloading due to rapid urban growth or commercial expansion in the Eastern areas, leading to load demands exceeding feeder design capacity, and reduced likelihood of protective device operation and equipment degradation;
(ii) constrained switching and network reconfiguration capabilities by EDSA—for instance, if the HV network serving the East lacks sectionalizing switches, fault isolation and restoration times would be prolonged, extending outage durations; or
(iii) maintenance gaps—deferred or infrequent preventive maintenance could allow minor issues (e.g., partial discharge, corroded connectors) to escalate into feeder-level failures.

Regardless of the underlying cause, these HV outages impose significant costs on MSMEs, including lost revenue, disrupted supply chains, and diminished customer confidence.

[2] Q4, 2024 contains data for only two months (November and December) as data collection began in November 2024.

The socio-economic and equity dimensions of SAIDI

The World Bank's assessment of urban poverty dynamics in Freetown reveals a spatialised pattern of deprivation, with levels of deprivation increasing with distance from the CBD. Non-housing dimensions of poverty are particularly pronounced in Eastern areas such as Hastings and Waterloo, reflecting broader structural inequalities in urban development. These spatialised poverty patterns are observable in our outage data. As shown in Figure 17, communities located in the East of the grid are disproportionately subject to prolonged MV outages. For MSMEs in these areas, the predominance of large, prolonged MV outages not only exacerbates existing electricity equity challenges but also reinforces their exposure to multidimensional poverty. Outages of this scale constrain operational continuity, reduce the capacity to invest in productivity-enhancing technologies, and limit access to broader markets.

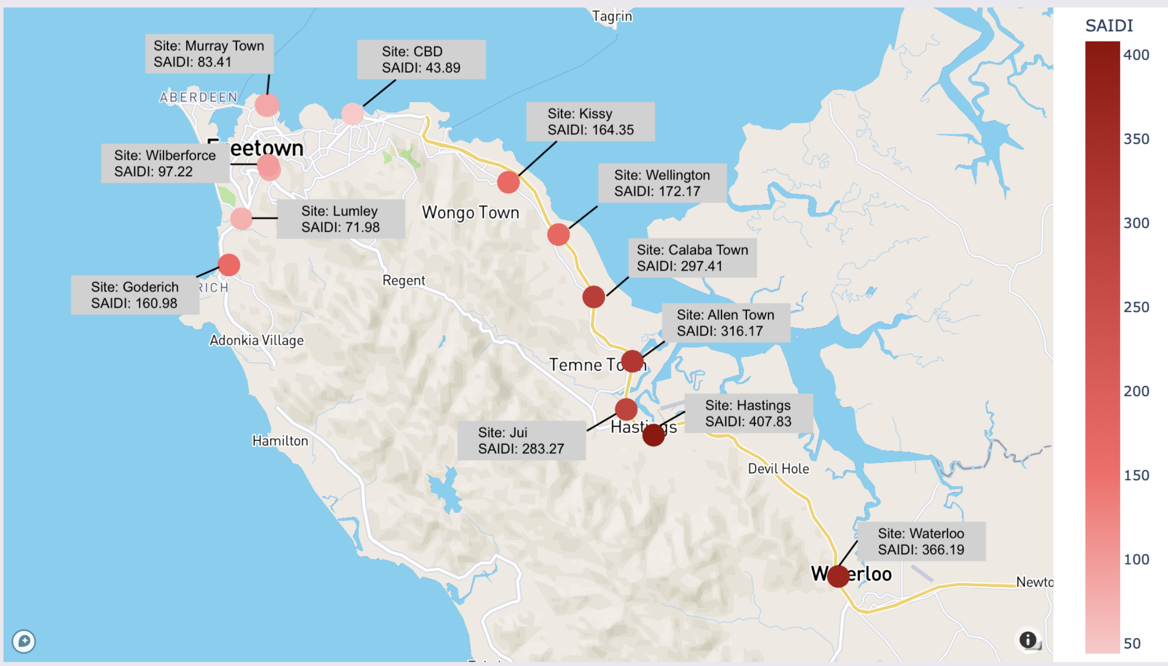

Figure 19: Average monthly SAIDI by site. SAIDI worsens when moving away from the CBD in either direction (i.e., towards Waterloo or towards Goderich).

Beyond immediate impacts on MSME operations, outages experienced by MSMEs in the East perpetuate economic marginalization as they restrict Eastern MSMEs' ability to consume electricity for productive uses and compete with MSMEs in the West or more affluent areas that experience fewer and smaller-scale outages. These outages also reflect deeper structural inequities in grid design, maintenance, and service prioritization where low-income clusters are both physically and infrastructurally more exposed to feeder- and substation-level vulnerabilities.

4.2.1.3 Power Outages Are Frequent

Our analysis shows that MSMEs experienced 6,195 interruptions over the course of the monitoring period. Both Eastern and Western MSMEs experienced similar patterns of interruptions with an average of 200 interruptions per quarter. The mean daily number of interruptions per area is greater than one, with Hastings, Jui, and CBD sometimes experiencing more than 10 interruptions in a day. In the Eastern area, MSMEs in Allen Town and Calaba Town experienced more interruptions than the other sites in the first quarter of monitoring. In the Western areas, MSMEs in Goderich experienced more interruptions than the other sites in the first quarter of monitoring, while MSMEs in Wilberforce and CBD experienced more interruptions in the second quarter of 2025.

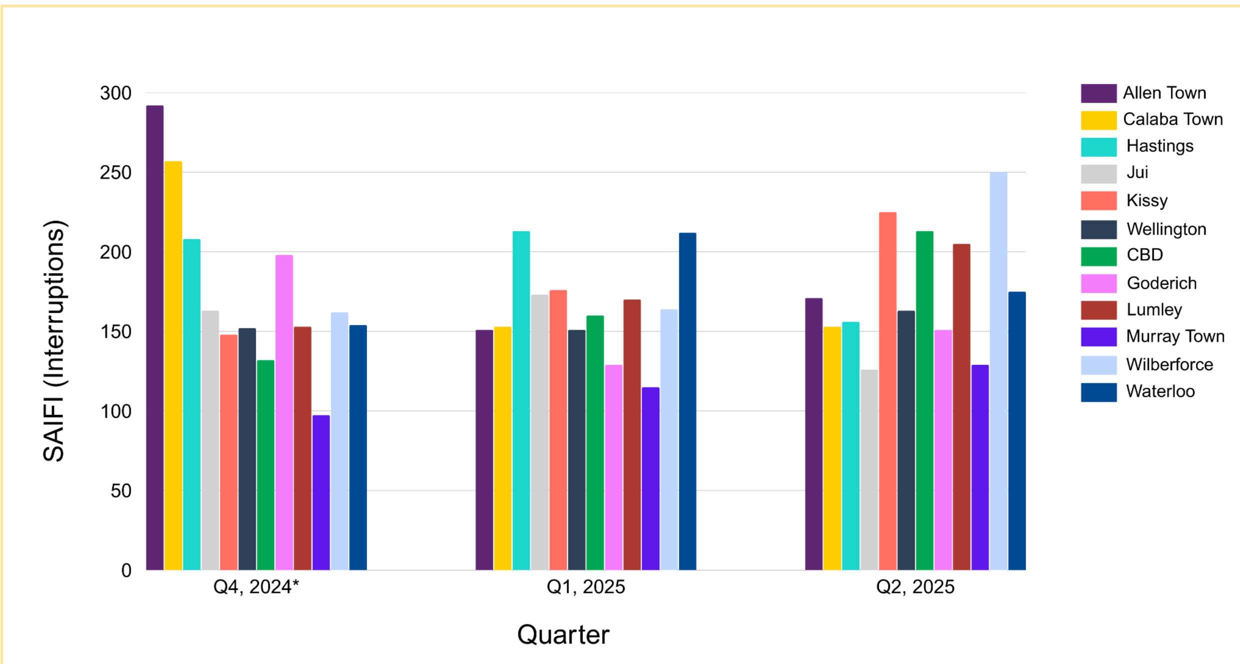

Figure 20: Quarterly[3] SAIFI by site (across both West and East). We see no significant variability in the distribution of SAIFI across the sites. No clear pattern emerges, in contrast to the SAIDI distribution.

MSME appliances like refrigerators are not designed to start and stop many times per hour. Frequent outages not only limit the capacity of the refrigerator's compressor to achieve meaningful cooling, they also limit the lifespan of the refrigerator, exposing the MSME to additional costs associated with appliance replacement or repair (Cissokho and Seck, 2013).

[3] Q4, 2024 contains data for only two months (November and December) as data collection began in November 2024

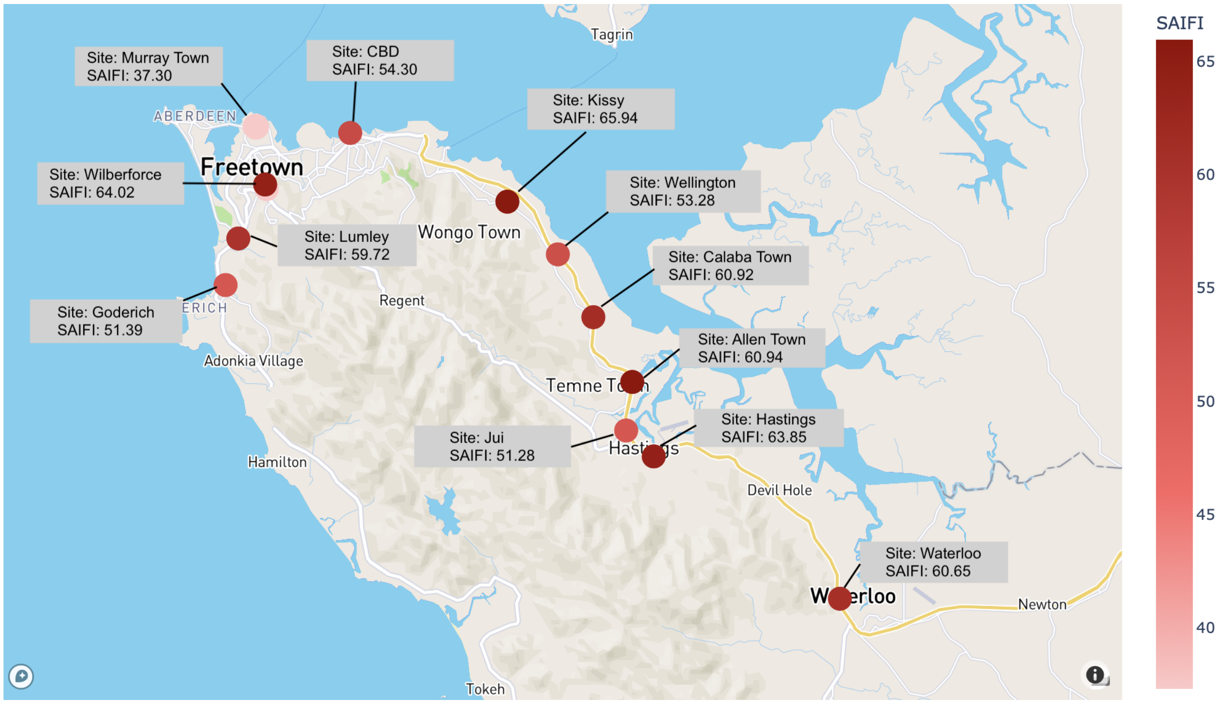

Figure 21: Average monthly SAIFI by site. The map shows no significant variability in the distribution of SAIFI across the sites. No clear geographic pattern emerges, in contrast to the SAIDI distribution.

4.2.1.4 Factoring in Seasonality in Observed SAIDI and SAIFI trends

In Sierra Leone, where hydropower contributes significantly to the energy mix, seasonal climatic variation in precipitation is often considered a determinant of grid reliability. As such, we assess the relationship between precipitation and the observed SAIDI and SAIFI levels. Our data provides nuanced insights into the performance of the grid under varying climatic conditions. As seen in Figure 22, our analysis of SAIDI reveals an inverse relationship with precipitation during the latter months of the monitoring period: SAIDI values decline between March and July as precipitation increases from near-zero to approximately 18 mm. This trend suggests that the onset of the rainy season may have contributed to improvements in grid reliability as greater water availability enhances Sierra Leone's hydropower generation capacity. Nevertheless, this pattern is not consistent across the entire monitoring period, indicating that precipitation alone does not fully account for variations in grid performance. Several factors may contribute to this inconsistency; for instance, infrastructure maintenance practices likely mediate the extent to which climatic conditions affect grid stability. Also, qualitatively, we found that precipitation did have dual effects: while moderate rainfall may have supported generation capacity, excessive or extreme rainfall events increased the risk of infrastructure damage, leading to service interruptions.

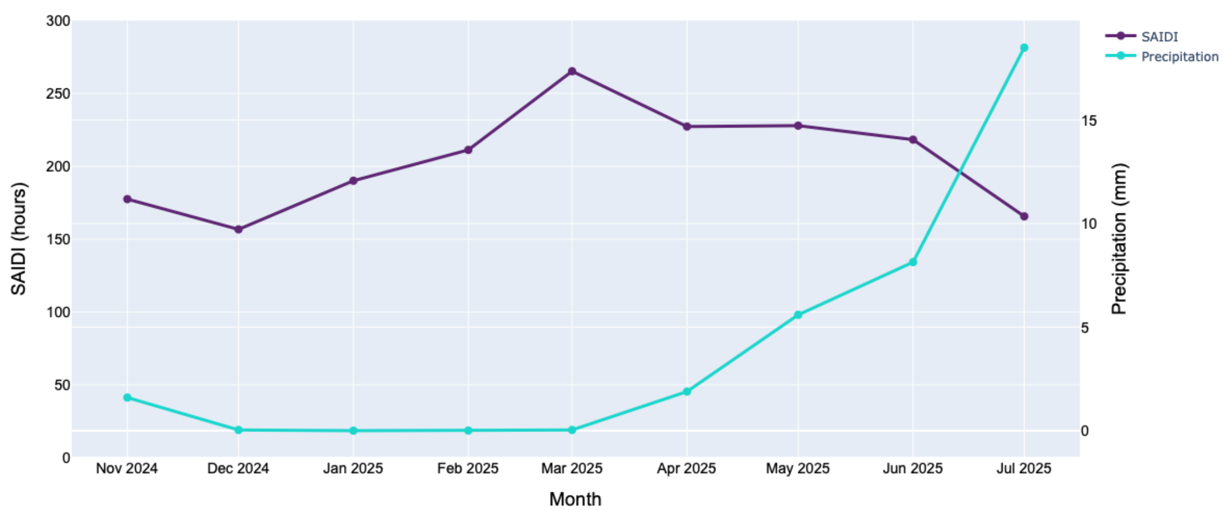

Figure 22: Monthly SAIDI vs. average monthly precipitation. The SAIDI vs. precipitation analysis reveals a notable inverse relationship during the latter months of the monitoring period, where SAIDI decreases from March to July as precipitation increases from near-zero to around 18 mm in July.

In contrast, our analysis of SAIFI against precipitation demonstrates no consistent correlation between interruption frequency and precipitation levels. Between December 2024 and March 2025, precipitation remained close to zero, yet SAIFI fluctuated substantially, ranging from 52.38 to 58.46 interruptions per customer. As precipitation increased from April to July 2025, SAIFI trends remained mixed: rising in April and May, falling sharply in June, and increasing again in July. These findings indicate that precipitation is not a reliable predictor of SAIFI. Instead, factors such as asset age and condition, maintenance, vegetation management, or demand patterns likely play more significant roles in predicting SAIFI performance.

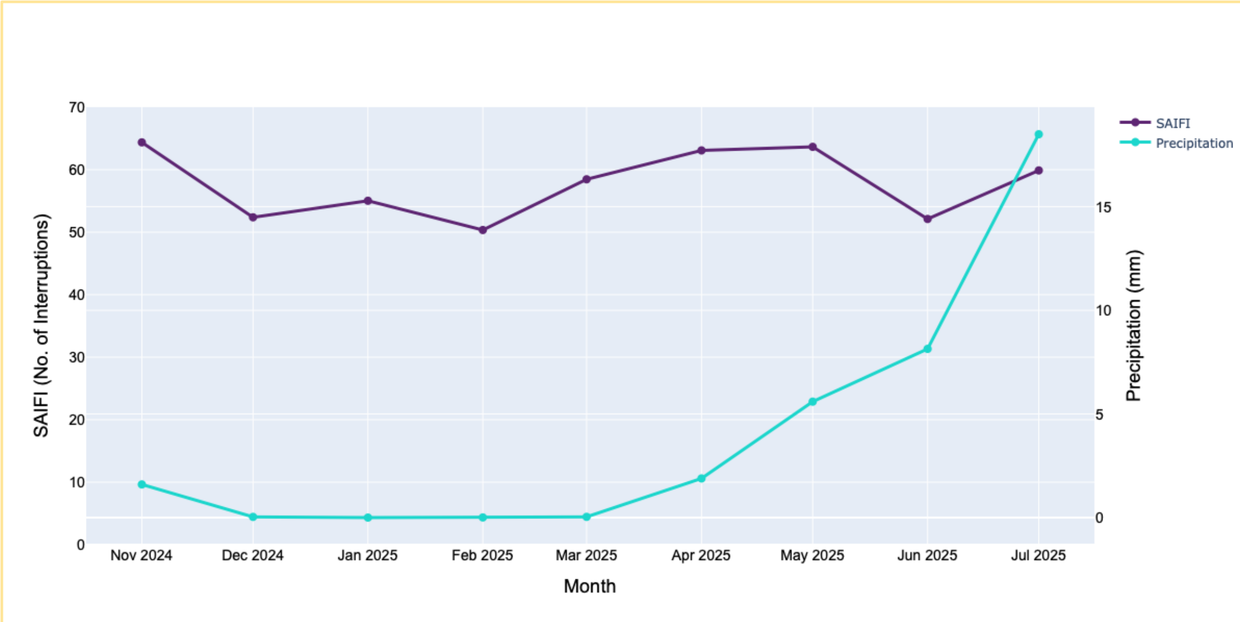

Figure 23: Monthly SAIFI vs. average monthly precipitation. The SAIFI vs. precipitation analysis shows no consistent correlation between interruption frequency and precipitation levels throughout the observation period.

SAIDI's partial sensitivity to precipitation during specific months, and SAIFI's lack of correlation, highlights the need for multidimensional assessments of reliability, incorporating both environmental variables (e.g., precipitation, temperature, extreme events) and system-specific factors (e.g., maintenance practices, demand variability, asset resilience).

4.2.1.5 Comparing MSME-Reported Outages with GridWatch-Measured Outages

Self-reported outage data from MSMEs provides valuable insights into the perceived impacts of electricity disruptions, such as sales and productivity losses. Respondents were asked to recollect outage durations and frequencies for the week prior to sensor installation at their premises. However, such retrospective reporting of outages is likely to be prone to recall and perception biases, which can lead to over- or under-estimation. To assess the reliability of such reports, we compared MSME-reported outage frequency and duration data with sensor-based measurements at two levels: within the week of sensor deployment and across nine months spanning November 2024 to July 2025 (Figures 24 to 27).

Our analysis reveals substantial differences between self-reported and sensor-reported data. For example, MSMEs in Waterloo reported the highest perceived rate of interruptions (21.75 outages per week), whereas as shown in Figure 24, sensor data for the week following deployment indicated a higher but closer frequency of interruption at 22.5 outages per week. On the other hand, in Allen Town, Goderich and Hastings, we see a huge difference between sensor measured SAIFI post deployment vs perceived SAIFI.

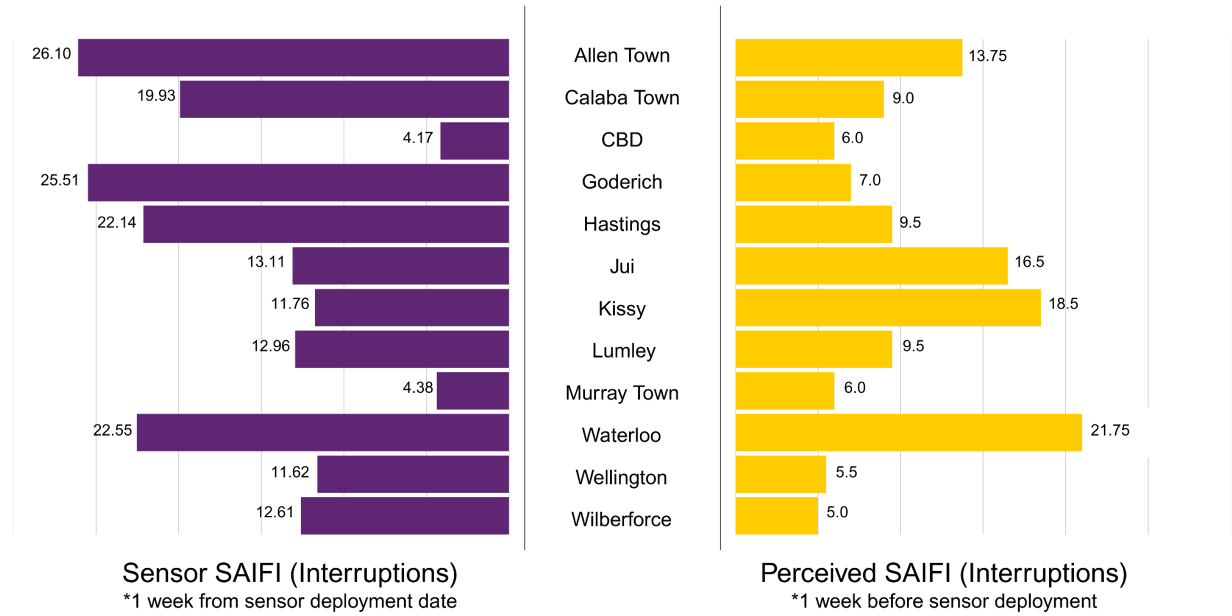

Figure 24: Weekly average sensor-measured SAIFI within the week of sensor deployment vs perceived SAIFI in the week prior to sensor installation for the 12 communities. The GridWatch data shows that MSMEs in Allen Town, Goderich and Hastings experienced twice the perceived SAIFI in the first week of measurement.

Given the differences in measurement timelines between the period of sensor deployment and the respondent recall period for PQR data, it was necessary to test whether the sensor measurements collected after installation were influenced by other forms of system-related biases, such as seasonality, localized infrastructure disruptions, or maintenance-related interruptions. To address this concern, we conducted a robustness check by comparing sensor trends across the entire monitoring period with perceived SAIFI and SAIDI (see Figures 25-27). We examined whether PQR patterns observed during the week following sensor deployment remained consistent throughout the monitoring period. This allowed us to assess whether early sensor measurements were representative of the monitored section of the grid or influenced by system anomalies that could compromise comparisons with survey-based recall data. While we acknowledge the limitations of the above strategy (i.e., our inability to match sensor and survey data for the same week), we believe that this approach ensures that our interpretation of the differences between survey and sensor data reflects genuine discrepancies in reporting and not an artefact of measurement timing.

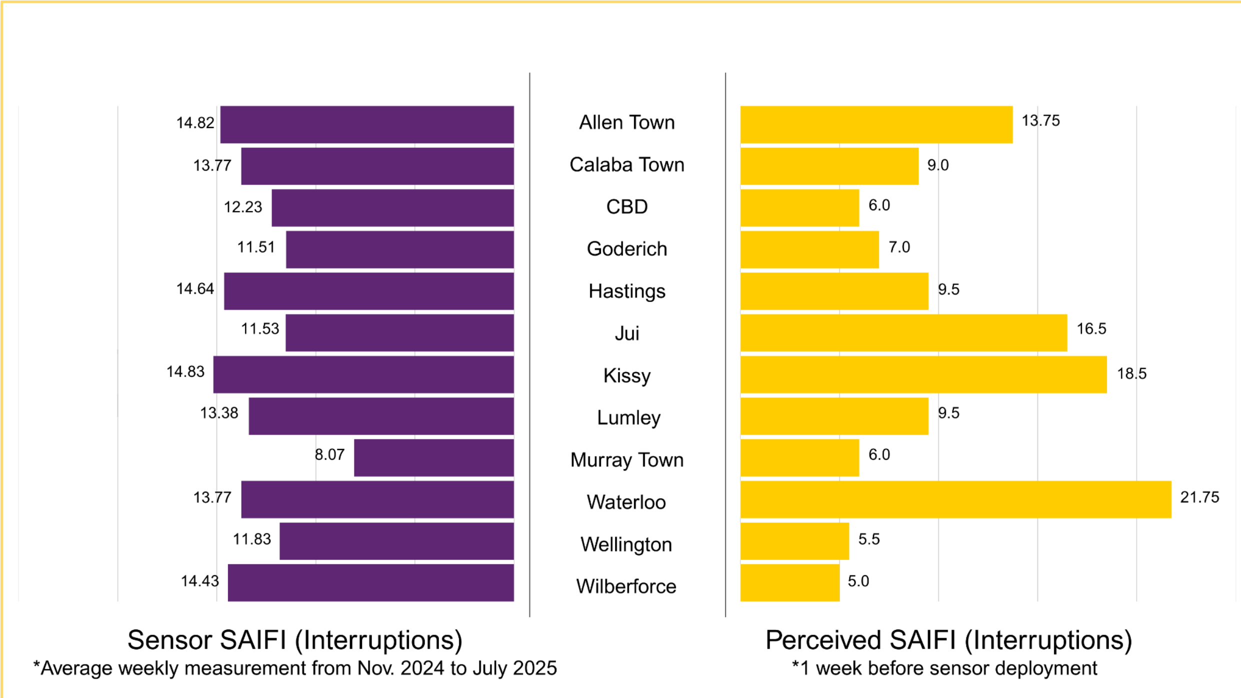

Figure 25: Weekly average sensor-measured SAIFI for the entire monitoring period (Nov. 2024 to July 2025) vs perceived SAIFI in the week prior to sensor deployment for the 12 communities. The data shows substantial variation between GridWatch's measurements and subjective experiences, with Waterloo MSMEs reporting the highest perceived interruptions (21.75 outages/week) despite moderate average sensor readings (13.77 outages/week) over the entire period of monitoring.

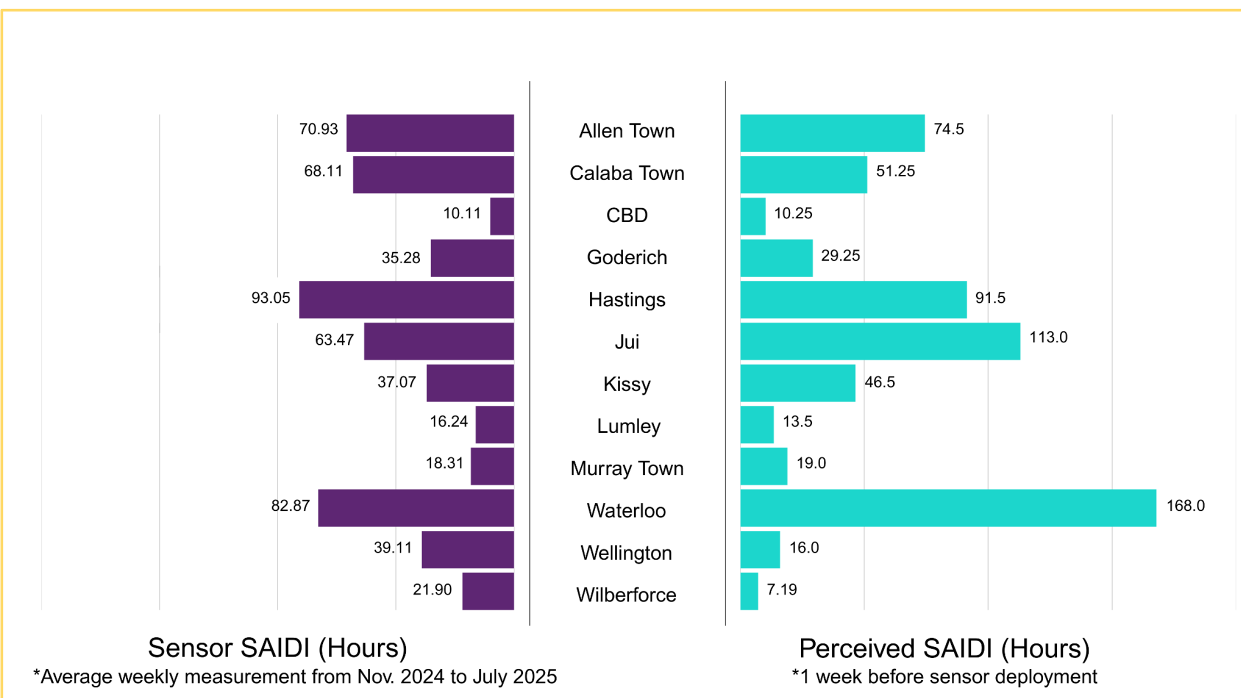

Figure 26: Weekly average sensor-measured SAIDI within the week of sensor deployment vs perceived SAIDI in the week prior to sensor deployment for the 12 communities.

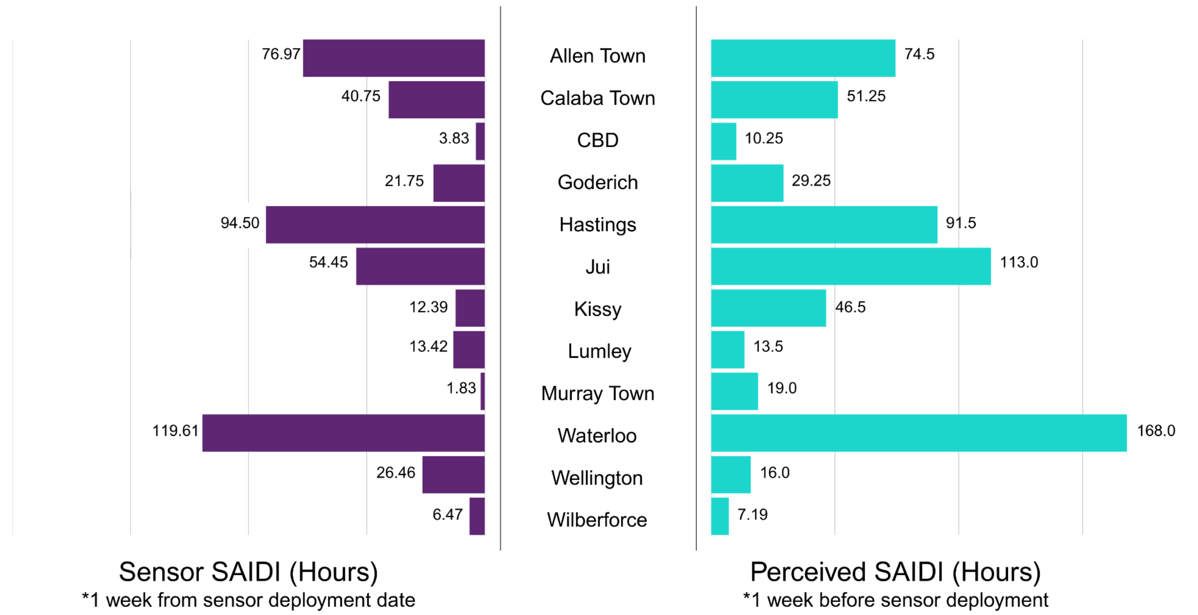

Figure 27: Weekly average sensor-measured SAIDI for the entire monitoring period (Nov. 2024 to July 2025) vs perceived SAIDI in the week prior to sensor deployment for the 12 communities. The data shows substantial variation between GridWatch's measurements and subjective experiences, with Waterloo residents reporting the highest perceived outage duration (168.0 hours, or the entire week), almost twice the average sensor readings (82.87 hours).

From the above data, we see no consistent correlation between sensor-derived KPIs (e.g., PQR) and self-reported outage experiences. These results underscore a fundamental methodological concern: self-reported data captures perceptions rather than actual grid performance. The observed overstatements likely reflect heightened sensitivity to voltage fluctuations, normalization of outages or misremembering the timing of events which can amplify perceptions of unreliability. In contrast, sensor data provides objective, precise, and verifiable measures of outage frequency and duration, offering a more accurate assessment of system performance and a reliable foundation for designing technical interventions.

The divergence between the two data sources underscores a critical point: human perception can exaggerate or understate the reliability of electricity supply relative to measured conditions. Yet, dismissing self-reported data altogether would overlook its distinct value. While sensor measurements establish the "hard" reality of system performance, self-reports capture the lived experience of electricity users—experiences that may shape business decisions and demand for service improvements. When combined with sensor data, self-reports provide a more holistic account of both technical performance and human impact. This is because surveys can reveal the human behaviors behind sensor data. For example, while collecting data in Ghana, we noticed that some sites recorded unexpectedly high outages. After checking in with participants through surveys, we discovered that these outages were not from the grid but were due instead to human behavior: Shop owners were switching things on and off in ways that mimicked outages. So while sensors are gold—precise, measurable, generalizable—and should be the priority, especially to capture the needs of a large population, surveys, even with their flaws, can help humanise the impact of the problem.

4.2.2 Assessing Voltage Quality and its Impacts on MSMEs

Voltage quality issues such as spikes and sustained sags (see Figure 28) are more nuanced than outages and relate to the nature of electricity when it is on, but their impacts can be devastating, with MSMEs reporting equipment burnout, low operational efficiency, and the need for voltage regulators or stabilizers. These challenges remain largely unquantified, limiting policymakers' and utilities' capacity to effectively target upgrades. In Table 4, below we summarise the average daily voltage quality experienced by MSMEs. Here we focus on 3 best- performing and 3 worst performing communities, for broader insights on all 12 communities monitored see Appendix 1.

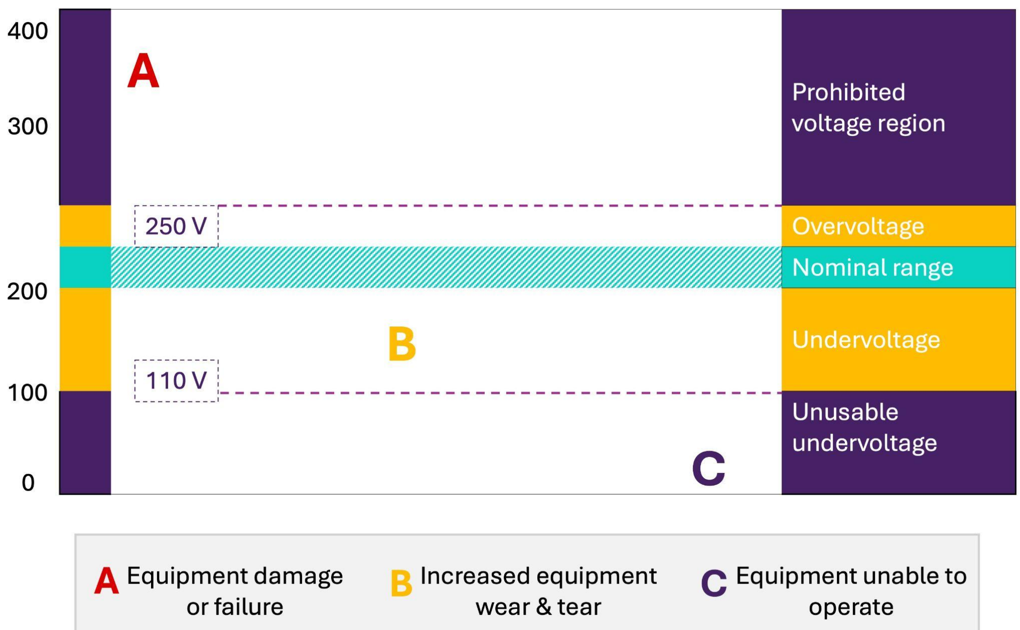

Figure 28: **Visual example of voltage range tolerance band**. Point A signifies over-voltage conditions where voltage is beyond the nominal band and detrimental to appliances. Point B describes undervoltage conditions where voltage sags trigger appliance stress. Point C reflects voltage conditions that make appliances inoperable.

4.2.1. Voltage Variance Across Monitored Segments of the Grid

The GridWatch voltage quality data reveals significant disparities in power quality standards across different sites. As observed with outages, MSMEs in the West (e.g., Wellington, Lumley, and Murray Town) receive voltage levels close to the nominal 230V standard with minimal undervoltage exposure. In contrast, MSMEs in the East (e.g., Hastings, Calaba Town, and Waterloo) experience severe voltage quality issues: Hastings customers receive only 190V on average and endure 6.6 hours of undervoltage daily. Interestingly, while customers in Wellington receive on average 230V, they also experience the worst overvoltage duration of 305 minutes per day. These findings indicate that while some areas maintain acceptable voltage quality, others suffer from chronic undervoltage that can damage equipment or excessive overvoltage that poses safety risks and ultimately leads to huge financial losses for the MSME.

Table 4: Average Daily Power Quality KPI Values for the 3 Best-Performing and 3 Worst-Performing Sites. For KPI values of all sites see Table 5 in the Appendix.

KPI	Definition	Unit	Site	KPI Value
Voltage Magnitude	Average voltage delivered to a customer (Nominal voltage in Sierra Leone is 230V)	Voltage RMS	Wellington	230.0
			Lumley	231.0
			Murray Town	234.0
			Waterloo	205.0
			Calaba Town	203.0
			Hastings	190.0
Daily Hours Undervoltage	Average daily number of hours a customer experiences voltage lower than 10% below the nominal value (230V)	Hours per day	Lumley	0.201 (12 min)
			Central Business District	0.206 (12 min)
			Murray Town	0.623 (37 min)
			Waterloo	4.05 (4 hr 3 min)
			Calaba Town	5.39 (5 hr 23 min)
			Hastings	6.60 (6 hr 36 min)
Daily Minutes Overvoltage	Average daily number of minutes a customer experiences voltage higher than 10% above	Minutes per day	Goderich	0.0
			Wilberforce	0.03

	the nominal value (230V)		Hastings	0.57
			Central Business District	45.9
			Waterloo	49.9
			Wellington	305 (5 hr 5 min)

Even in areas with relatively stable averages, individual readings frequently fall outside the acceptable range, both above and below the ±10% threshold around 230V. The presence of such readings across multiple months and sites points to chronic power quality challenges rather than isolated anomalies.

4.2.2 Extreme Voltage Events are Frequent

We observed several extreme voltage events of varying nature. We found smaller undervoltage excursions (below 190V), larger undervoltage excursions that result in appliance inconvenience in the form of improper operations (below 100V), and very high spikes (exceeding 300V) that result in rapid appliance failure and violate IEEE/IEC voltage thresholds. As seen in Figure 28, voltage sags below 100V render electricity unusable and will likely cripple MSMEs' operational capabilities. The effects of these sags are also cumulative as they draw higher current from compressors or motors of appliances like refrigerators. Similarly, the observed voltage spikes above 300V are not tolerable by most appliances and often result in improper operation, increased equipment wear and tear, and cumulative degradation or damage. For example, in Murray Town (see Figure 29 and the case study below), sustained overvoltages with high magnitudes were more destructive than sags, overstressing appliance components and resulting in immediate appliance failure. Local business owners reported appliance damage corresponding with periods where overvoltage excursions occurred. These real-world impacts underscore the need for more stable power supply as a prerequisite for economic resilience in these communities.

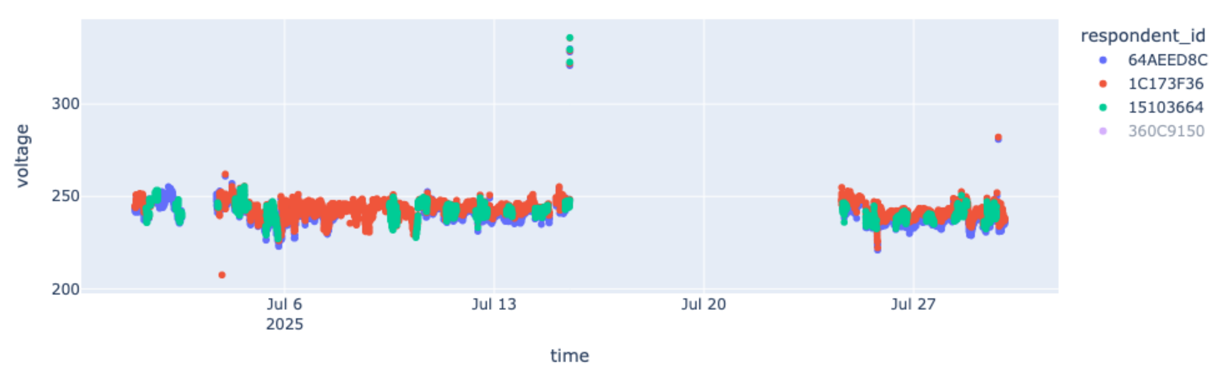

Figure 29: MSMEs in Murray Town experienced voltage spikes of up to ~336V on July 15th before an outage that lasted until July 24th. The blank spaces with no reported voltage indicate power outages.

Quantifying voltage quality issues and estimating their effect on productivity separately from outages provides data useful for many different stakeholders. For example, with this data, (i) MSMEs can perform cost analysis of decreased equipment efficiency per service operations; (ii) equipment/appliance designers and manufacturers can consider sensitivity to voltage variations alongside other design factors like equipment efficiency; and (iii) utilities can optimise their use of existing voltage regulation equipment or strategically invest in voltage regulation to minimise steady-state voltage excursions.

Stories from the Ground: What Voltage Surges Mean for MSMEs

Voltage instability (i.e., surges, sags, and fluctuations) is more than a technical issue—it has direct consequences for businesses that depend on electricity for daily operations. We present two brief cases from our study in which momentary and sustained voltage surges damaged MSME appliances and equipment, illustrating these costs in practice.

Allen Town

On July 23, 2025, at around 11:45pm local time, one MSME in Allen Town began to experience sustained overvoltage (i.e., 326–344 V) for approximately one hour. This voltage surge caused at least NLe 1,405 ($60) in direct damages to appliances and equipment at the business and rendered the following items useless:

Damaged Items	Estimate Cost to Replace Item (USD)
Power strip	NLe 450 ($19)
5 light bulbs	NLe 125 total ($5)
5 phone chargers	NLe 750 total ($32)
1 double wall outlet	NLe 80 ($3)
Cables for 2 ceiling fans	Cost not ascertained

Figure 30: The double wall outlet damaged as a result of a sustained voltage surge at a business in Allen Town.

During initial sensor installation, the business owner reported being "somewhat satisfied" with their grid power and reported spending less than NLe 99 ($4) on their prepaid electricity meter per week. They reported having experienced voltage issues in the past that had damaged equipment and appliances at the business, including an electric fan, light bulbs, television, and refrigerator, and had spent at least NLe 500 ($21) to repair the damaged goods. The three other sampled businesses in Allen Town connected to the same distribution transformer did not experience the voltage surge, indicating that the surge could have potentially affected a single phase.

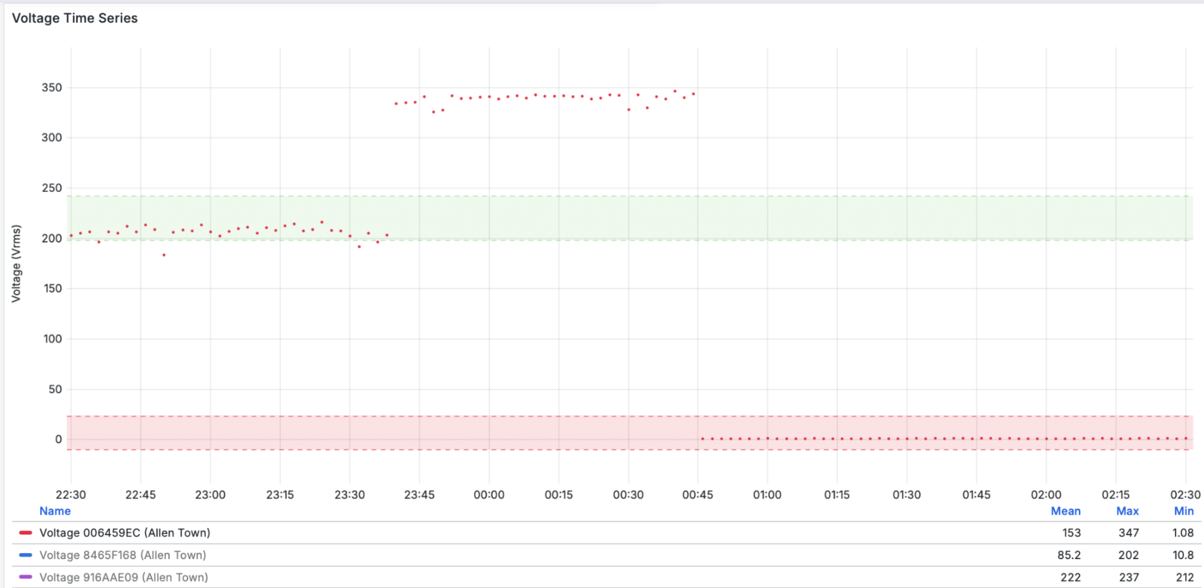

Figure 31: A business in Allen Town experienced sustained overvoltage of 326–344 V, beginning at around 11:45pm local time on July 23, 2025, and lasting until approximately 12:45am local time on July 24 (approximately one hour).

Murray Town

On July 15, 2025, at around 12:30pm local time, three businesses in Murray Town experienced a voltage spike (i.e., 321–330 V) for approximately six minutes. This voltage spike caused at least NLe 1,490 ($63) total in direct damages to appliances and equipment at the three business and rendered the following items useless:

Damaged Items for Business #1	**Estimate Cost to Replace Item (USD)**
16mm cable connected to the EDSA meter	NLe 500 ($21)
Damaged Items for Business #2	**Estimate Cost to Replace Item (USD)**
6 light bulbs	NLe 180 total ($8)
Damaged Items for Business #3	**Estimate Cost to Replace Item (USD)**

7 light bulbs	NLe 210 ($9)
Radio	NLe 600 ($25)

After this voltage spike, business owner #3 reported purchasing a stabilizer for their business at a cost of NLe 700 ($30), while business owner #2 shared that financial constraints keep them from purchasing a voltage stabilizing device.

The business owners reported that the voltage spike seems to be linked to unstable grid output and expressed concern over the ability of EDSA to mitigate against future voltage spikes and replace the affected distribution transformer.

Figure 32: A wall outlet (left) and radio (right) were damaged by a voltage spike at three sampled businesses in Murray Town.

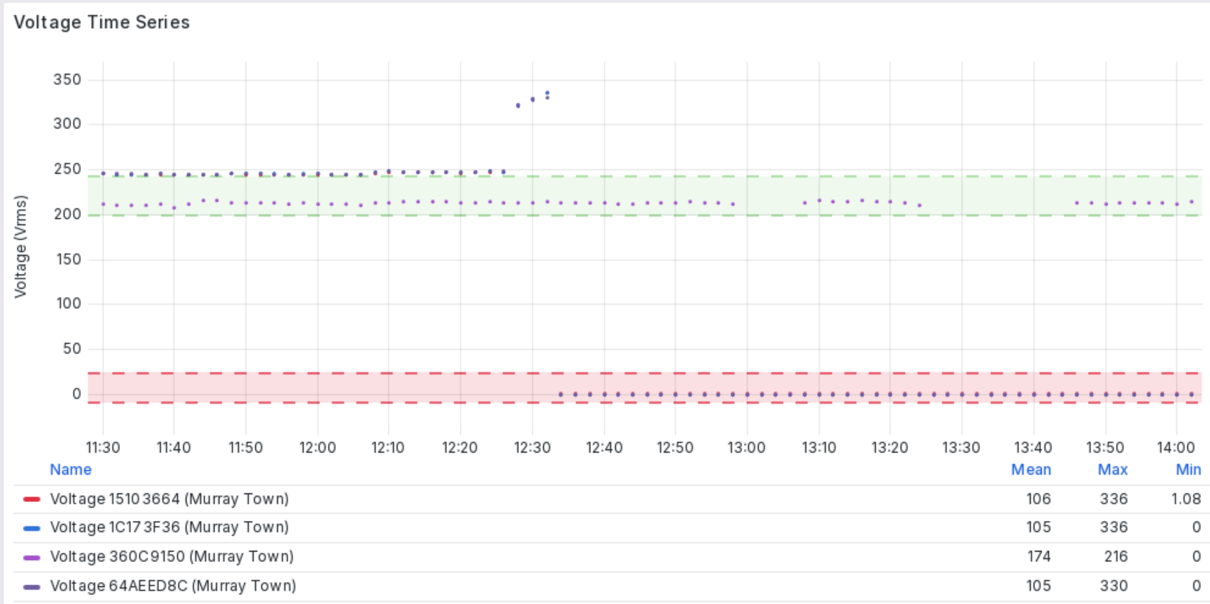

Figure 33: On July 15, 2025, at approximately 12:30pm local time, three out of four sampled businesses in Murray Town experienced a voltage spike of 321–330 V that lasted about 6 minutes.

4.2.3 The Monetary Cost of Outages to the National Utility (EDSA)

As discussed in Section 2.1, the value of lost load (VoLL) and the customer damage function (CDF) have been widely employed to capture customers' willingness to pay for reliability and to assess the economic consequences of electricity outages. While these indicators are relevant, in this section, we focus on an equally important dimension: the costs borne by utilities due to outages (i.e., monetary losses from unserved energy). Below we present our estimates of the cost of unserved energy in Freetown and the potential benefits to EDSA from investment in grid reinforcements.

4.2.3.1 Estimated Cost of Outages to EDSA

The following assumptions and data informed our estimates of unserved energy in Freetown. First, as shown in Table 5, EDSA's MSME customers are not a homogeneous group. Instead, they exhibit significant variation in annual electricity consumption, with some businesses likely consuming more kilowatt-hours (kWh) than others. Despite this variation, all MSMEs are subject to a uniform tariff of USD 0.25 per kWh, as prescribed by the EDSA tariff structure. As such, the value of unserved energy can be approximated by calculating the kWh that would have been consumed in the absence of supply interruptions. Second, as shown in Section 4.2, both the duration and frequency of service interruptions vary across different geographical locations in Freetown. This spatial variation implies that outage impacts are location-specific, and must be disaggregated to produce more accurate estimates of unserved energy. Third, the timing of interruptions also plays a critical role in determining their economic impact. Outages occurring during peak business hours or production cycles tend to mean significantly less kWh consumed and less revenue for utilities compared to interruptions during off-peak periods. Consequently, temporal variation must be considered to capture the full economic consequences of unserved energy.

To generate estimates on likely kWh consumed, we rely on survey data collected during the GridWatch deployment which indicate that MSMEs spend approximately 150 Sierra Leonean Leones (SLE), or USD 6.52, per week on electricity[4]. The $6.52 weekly electricity cost is divided by $0.25 per kWh, which gives a weekly energy consumption of 26.08 kWh [energy used = weekly spend/ Tariff = 6.52/0.25 = 26.08 kWh/week]. This comes to a total of 1017.12kWh for the duration of the GridWatch monitoring period (9 months).

To calculate average hourly load, we divide weekly consumption by total hours in a week [average load = 26.08/168 hours in a week] which corresponds to an average hourly load of about 155 W. However, from our sample, we have two types of MSMEs: those that operate refrigeration appliances all 24 hours, and others who primarily operate appliances during typical business hours—around 60 hours per week. For this analysis, we assume that most businesses operate at 60 hours a week, and based on this assumption, we expect the average load per hour to be about 0.434 kWh [26.08/60]. Finally, to estimate unserved energy, we multiply the assumed hourly load per customer by the observed duration of outages recorded for the entire monitoring period (see Table 5). We acknowledge that the data on MSME energy use is based on assumptions and our consumption estimates would be more robust if derived from utility data measured at the transformer or feeder level.

Table 5 presents an estimate of un-served energy per customer over the 9 month monitoring period in USD. It shows the cost of SAIDI for the monitoring period per MSME and illustrates the wide variation in SAIDI cost per site.

Site	SAIDI (hours)	Unserved energy per MSME (kWh)	Unserved energy for monitored MSMEs in a site (kWh)	Cost of unserved energy to EDSA (USD per site)
Hastings	3,691.75	1,602.20	6,408.80	1,602.20
Waterloo	3,572.00	1,550.24	6,201.00	1,550.24
Goderich	1,513.82	657.00	268.00	657.00
Calaba Town	2,773.59	1,203.70	4,814.80	1,203.70
Wellington	1,429.66	620.47	2,481.88	620.47
Kissy	1,333.46	578.72	2,314.88	578.72
Murray Town	633.00	274.72	1,098.88	274.72
CBD	387.95	168.37	673.48	168.37
Jui	2,514.03	1091.00	4,364.00	1,091.00
Allen Town	2,919.42	1267.00	5,068.00	1,267.00

[4] Converted at 0.043478 SLE to USD. This consumption figure is reflective of suppressed demand as Sierra Leone has one of the lowest electricity per capita consumption in the world.

Lumley	655.21	284.36	1,137.44	284.36
Wilberforce	870.19	377.66	1,510.64	377.66
Total	**22,294.08**	**9,675.44**	**36,341.8**	**$9,675.44**

Scenario Analysis: Translating findings to assess impacts of outages on EDSA revenue

As shown from data from the Freetown City Council, the city currently has about 32 markets. To see the likely impacts of SAIDI for EDSA's revenue across these markets we made the following assumption: using the data from our real time monitoring, we pegged unserved energy from SAIDI to an average of 804 kWh per MSME over a 9-month period and at the prevailing tariff of USD 0.25/kWh to create three scenarios.

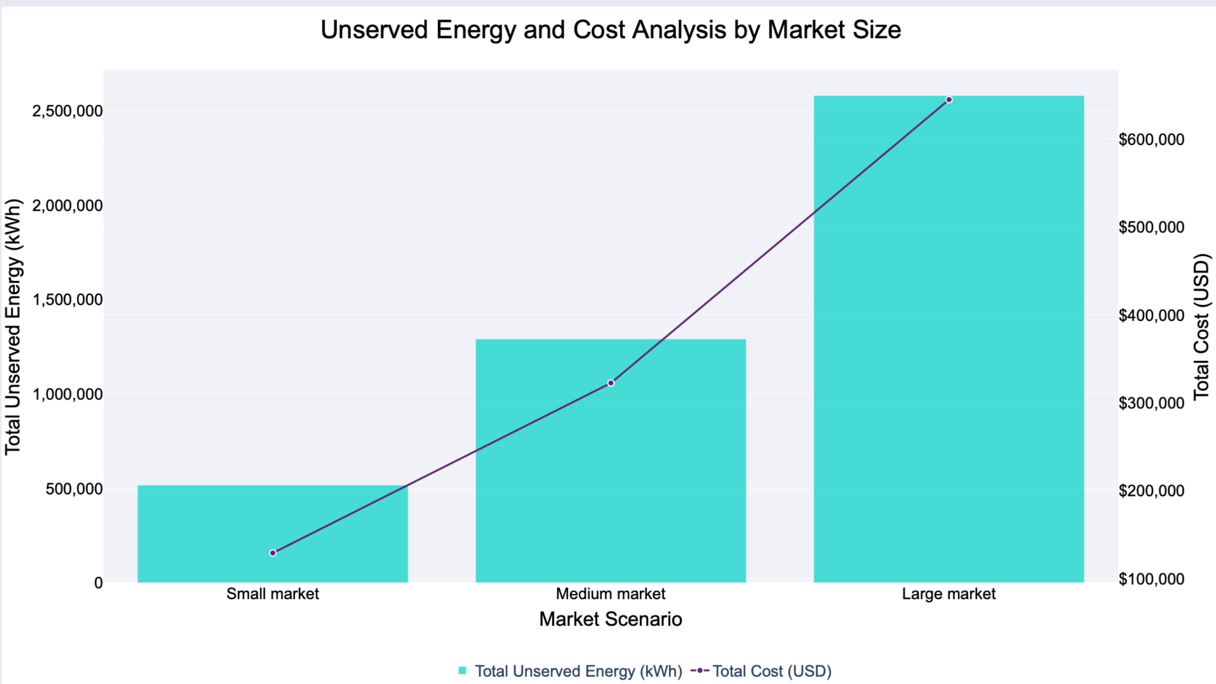

Figure 34: Modelled cost scenarios showing the $ value lost by EDSA from unserved energy across three types of market clusters in Freetown.

In scenario 1 ("small market"), we assume an average of 804 kWh in unserved energy per MSME over a 9-month period, at the prevailing tariff of USD 0.25/kWh. We also assume there are 20 MSMEs per market. With these assumptions, cumulative losses to EDSA amount to USD 128,960 over a nine-month period. In Scenario 2, the "medium market," we assume 50 MSMEs per market. The estimated losses due to SAIDI over the same period total USD 322,400. In Scenario 3, the "large market," with 100 MSMEs per market, the estimated losses rise to USD 644,800. These costs are comparable to the potential expenses from targeted infrastructure rehabilitation projects. Please see Table 6 in the Appendix for details.

This analysis shows that reduced SAIDI is not only a technical goal but an economic imperative, as every hour of avoided outage directly prevents substantial financial losses for EDSA. Reducing SAIDI by even 20% could save EDSA between USD 64,000 and USD 128,000 over a 9-month period(depending on market scale). For EDSA, framing SAIDI reduction in monetary terms strengthens the financial case for distribution upgrades that are likely to rapidly pay for themselves through avoided unserved energy costs.

5. Policy Implications

As demonstrated above, the nature and scale of PQR problems in Freetown are linked to a multitude of operational issues for MSMEs and, by extension, EDSA. While our granular PQR data draws attention to these issues, it also offers technical and policy pathways that could be adopted to address these challenges. Below we provide grid design options and policy changes that energy stakeholders could adopt to address the observed challenges.

Feeders located in Eastern Freetown are "poor power quality hotspots" and should be prioritised for more granular power quality monitoring and targeted upgrades. Given the stark disparity in power quality between the Eastern and Western grids of Freetown, the Eastern feeders should be formally designated as a "Poor Power Quality Hotspot." This prioritization will allow the regulator—the Electricity and Water Regulatory Commission (EWRC)—and EDSA to allocate monitoring and investment resources and attention where they are most needed. For example, the data presented in Table 5 on un-served energy per customer over the 9-month monitoring period could be used as a ranking tool to identify for immediate intervention the top 3–5 feeders causing the greatest economic losses. To provide more granularity, the MoE, EDSA, or other energy-sector investors could deploy additional power-quality sensors on these feeders, to identify the most overloaded segments and enable EDSA's rapid-response crew to conduct emergency repairs and reconductoring. Fast-tracking upgrades on these feeders and introducing structural fixes such as transformer replacements or capacitor banks will reduce outages, improve voltage stability, and directly support local businesses that are most adversely affected. Beyond the eastern corridor of the grid, the MoE and EDSA could also expand feeder-level monitoring infrastructure across Freetown to continuously capture voltage and outage data. Such citywide monitoring would ensure that electricity investments deliver the maximum social and economic benefit per dollar spent.

Energy sector stakeholders must deploy power-quality monitoring tools to enable data-driven grid governance. As shown from our analysis, effective poor-PQR mitigation requires precise, real-time data that enables EWRC to not only identify SAIDI and SAIFI hotspots but also capture the severity of voltage fluctuations that damage appliances or equipment. PQR monitoring ensures that issues are identified before they escalate into prolonged outages or widespread equipment damage. Beyond its reactive benefits of faster fault isolation and restoration, over time the collected data can also guide predictive maintenance programs, reducing costs and improving grid reliability. Such data also capacitates the regulator to establish new regulatory innovations around network performance improvements. For instance, with access to real-time monitoring, EWRC could institute a PQR monitoring mandate for feeders serving significant commercial clusters and establish a compensation/liability framework for verified appliance damage due to utility-side PQR failures, or even establish performance-based incentives that rewards EDSA for reducing unserved energy and voltage excursions. Such regulatory innovations would not only incentivise EDSA to actively manage power quality but also empower businesses, investors, and EWRC to monitor trends and ensure compliance.

MSMEs must be protected via appliance-damage mitigation measures to foster economic equity. MSMEs in high-outage areas are disproportionately impacted by voltage fluctuations, leading to equipment damage and financial loss. To address this, the Government of Sierra Leone, the Small and Medium Enterprise Agency (SMEDA), and EWRC could adopt mitigation strategies such as a utility-administered compensation fund, funded by a modest tariff surcharge, to reimburse businesses for verified utility-driven, voltage-related appliance damages, or a subsidy program for surge protectors, voltage regulators, and backup solutions. Such programs should be supported with training for MSMEs on managing PQR risks and investing in energy-efficient appliances. EWRC could also empower MSMEs to report power-quality issues and establish a streamlined reporting channel for appliance damage, allowing businesses to quickly document losses and request support. EWRC could draw on comparative models like India's state- Compensation Plan for Temporary Damages scheme. These measures would provide immediate relief to MSMEs, encourage investment in protective equipment, and help build trust between the utility and the business community.

Unserved-energy cost must be integrated into grid investment prioritisation and planning. Future grid investments should be guided by a clear economic rationale that considers reliability, quality, and economic impacts. As a starting point, the MoE and EDSA could leverage sensor-generated data on the economic costs of unserved energy to prioritize feeders for upgrades. In this scenario, every candidate feeder or asset investment is ranked by the expected unserved-energy cost avoided per dollar invested. This ensures that limited resources are directed toward projects that yield the highest return in terms of service reliability and economic benefit. Over time, such a systematic approach will optimise grid performance, enable cost reflective tariff allocation, reduce business losses due to outages, and create a transparent decision-making framework that regulators, investors, and stakeholders can understand and support.

6. Conclusion

This study began by diagnosing a flagrant dearth of evidence on the impacts of outage and voltage quality issues on MSME productivity in LICs across SSA. Specifically, we found that this evidence gap could be tied to (i) the absence of high-resolution, real-time monitoring tools, leading to methodological choices that potentially misidentify the scale of outages and voltage quality issues, and (ii) the exclusion of voltage quality in cost analysis which, by extension, limits economic valuations of electricity-quality impacts on MSME productivity. Our research addresses both gaps by generating real-time information on outage and voltage quality issues that can be integrated into electricity regulatory and utility planning exercises in Sierra Leone. We further generate potential pathways to develop new estimates on the cost of poor PQR to the electricity sector.

Finally, we note that, given the novelty of the MSME-PQR data generated in this project as a first-of-its-kind in an LIC, there are limitations to this data. Our sample size of 48 MSMEs limits our capacity to draw broader insights on the impacts of PQR on MSMEs. And due to our selection strategy, we sampled only grid-connected MSME customers, limiting our ability to draw conclusions about MSMEs' use of alternative energy sources to address PQR challenges.

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Appendix

Table 1: MSME-related Survey Questions

Survey Question	Available Responses
What industry best describes this business?	*Small shop (Groceries: packaged foods or drinks, toiletries, etc.), Small shop (electronics items), Small shop (clothing/cloth items), Small shop (energy items: kerosene, charcoal, etc.), Small shop (other), Selling food (meat or fish products / butcher), Selling food (agricultural produce/vegetables), Selling food (take-away/ready to eat, no seats), Selling food (Restaurant/Café with seats), Selling food (Bulk: Mill/processing grains, maize, flour, etc.), Selling food (other), Other: Pharmacy / shop for medical items, Commercial: Computing services (printing, make CD's, etc.), Commercial: Clerical work (accounting, legal advice, notary, etc.), Commercial: Electronics services (technician, repair broken devices, etc.), Commercial: Car repair/mechanics shop, Commercial: Barber, hairdresser, or beauty shop, Commercial: Tailor, sowing, or seamstress, Commercial: Clothes washing, Commercial: Shoe maker/ Cobbler/ Shiner, Commercial: Welding, Commercial: Carpentry, Commercial: Brick baker/ stone dresser / Masonry, Commercial: Plumbing, Commercial: Electric work, Commercial: Other*
Overall, how satisfied are you with the quality of EDSA light at this location?	*1 = very satisfied, 2 = somewhat satisfied, 3 = neither satisfied nor dissatisfied, 4 = somewhat dissatisfied, 5 = very dissatisfied*
In a typical WEEK, how much do you spend on EDSA light at this location?	*0 Nle to 99 Nle, 100 Nle to 499 Nle, 500 Nle to 999 Nle, 1,000 Nle or over, don't know, refused to answer*
In the last week (last 7 days), how many EDSA outages did you experience at this location?	*open ended integer value*
For how long does each of these EDSA power outages usually last?	*open ended integer value with unit*
Is there a meter that this location pays directly?	*postpaid meter, prepaid meter, no meter*

Does your business experience bad light?	*yes or no*
If yes, does your business have problems operating because of blackouts or bad light?	*yes or no*
Because of bad light, which of your appliances or equipment are you unable to use?	*the appliances or equipment that the respondent says are recorded*
Have blackouts or bad light damaged equipment or appliances you use at this location?	*yes or no*
If yes, which appliances or equipment have been damaged by bad light?	*the appliances or equipment that the respondent says are recorded*
Have you taken any actions to repair the damaged appliances or equipment?	*yes or no*
If "yes", how much in total did you spend repairing this appliance(s) or equipment?	*open ended integer value*

Table 2: Average Daily Reliability KPI Values Across the Entire Sampled Network

KPI	Definition	Unit	Site	KPI Value
Daily SAIDI	Average cumulative outage time experienced by a customer.	Hours per day	Central Business District	1.48
			Lumley	2.37
			Murray Town	2.75
			Wilberforce	3.23
			Goderich	5.09
			Kissy	5.45
			Wellington	5.62
			Jui	9.19
			Calaba Town	9.87
			Allen Town	10.4
			Waterloo	11.9
			Hastings	13.3
Daily SAIFI	Average number of outages experienced by a customer.	Number of interruptions per day	Murray Town	1.18
			Goderich	1.67
			Wellington	1.69
			Jui	1.73

			Central Business District	1.78
			Lumley	1.97
			Calaba Town	1.99
			Waterloo	2.00
			Wilberforce	2.11
			Hastings	2.12
			Allen Town	2.15
			Kissy	2.19
Daily CAIDI	Average duration of any single outage experienced by a customer.	Hours per day	Central Business District	0.83
			Lumley	1.20
			Wilberforce	1.53
			Murray Town	2.33
			Kissy	2.49
			Goderich	3.05
			Wellington	3.33
			Allen Town	4.84
			Calaba Town	4.96
			Jui	5.31

			Waterloo	5.95
			Hastings	6.27

Table 3: The Intersection Between Experienced Frequency of Outages and Operational Impacts

Scenario	PQR Role	Equipment Outcome
High SAIFI, low damage reported	Strong protections, resilient equipment, mild voltage shift	Business continues mostly unaffected
Low SAIFI, high damage reported	Violent voltage disturbances, lack of protection	Frequent breakdowns
Medium SAIFI, variable damage	Depends on equipment sensitivity, location, lines, investment	Mixed outcomes

Table 4: Voltage challenges and their likely impacts on appliances

Voltage impact type	Likely Impact	Spikes	Sags	Observed in Freetown
Reduced appliance performance	Reduced luminosity of incandescent and fluorescent bulb, premature failure of bulbs due to flickering from insufficient voltage		X	X
Reduced equipment efficiency	Transformer losses and decreased efficiency	X		
Increased wear/tear	Shorter lifetime of incandescent light bulbs	X	X	X
	Flickering of fluorescent bulbs		X	X
Inconvenience	Appliance stops working but may resume to work after voltage returns within acceptable range	X	X	X

	Increased appliance sensitivity to voltage sags		X	X
	Tripping of commercial appliance	X	X	X
	Stalling of refrigerator motors		X	X
Appliance Damage	Failure of appliance built-in surge protective devices		X	X
	Tripping of internal appliance fuses	X		X
	Decreased efficiency and eventual failure of surge protective devices	X		X
	Increased sensitivity to voltage spikes	X		X
	Appliance failure	X		X

Table 5: Average Daily Voltage Quality KPI Values Across the Entire Sampled Network

KPI	Definition	Unit	Site	KPI Value
Voltage Magnitude	Average voltage delivered to a customer (Nominal voltage in Sierra Leone is 230V)	Voltage RMS	Wellington	230.0
			Lumley	231.0
			Murray Town	234.0
			Wilberforce	223.0
			Central Business District	242.0

			Kissy	222
			Goderich	212
			Jui	210
			Allen Town	208
			Waterloo	205.0
			Calaba Town	203.0
			Hastings	190.0
Daily Hours Undervoltage	Average daily number of hours a customer experiences voltage lower than 10% below the nominal value (230 V)	Hours per day	Lumley	0.201 (12 min)
			Central Business District	0.206 (12 min)
			Murray Town	0.623 (37 min)
			Kissy	1.51 (1 hr 30 min)
			Wilberforce	1.82 (1 hr 49 min)
			Wellington	2.18 (2 hr 10 min)
			Jui	2.63 (2 hr 37 min)
			Goderich	3.50 (3 hr 30 min)
			Allen Town	3.73 (3 hr 43 min)
			Waterloo	4.05 (4 hr 3 min)
			Calaba Town	5.39 (5 hr 23 min)

			Hastings	6.60 (6 hr 36 min)
Daily Minutes Overvoltage	Average daily number of minutes a customer experiences voltage higher than 10% above the nominal value (230 V)	Minutes per day	Goderich	0.0
			Wilberforce	0.03
			Hastings	0.57
			Lumley	0.80
			Allen Town	0.93
			Calaba Town	1.02
			Jui	1.04
			Murray Town	4.30
			Kissy	7.14
			Central Business District	45.9
			Waterloo	49.9
			Wellington	305 (5 hr 5 min)

Table 6: Three Modeled Scenarios for Estimated Financial Costs for EDSA in Unserved Energy to Markets.

Scenario	MSME per market	Total MSME (32 markets)	Unserved energy per MSME (kWh / 9 months)	Total unserved energy (kWh)	Tariff (USD/kWh)	Total Cost (USD)
Small market	20	640	806	515840	0.25	128,960
Medium market	50	1600	806	1289600	0.25	322,400
Large market	100	3200	806	2579200	0.25	644,800

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