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Internet of Things could shape healthcare facility electrification: Evidence from the Democratic Republic of the Congo

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ABSTRACT

Modern health service delivery in energy-poor geographies increasingly relies on distributed and renewable energy technologies like solar and hydroelectric power to offset expensive and polluting diesel generation. While recent funding commitments to health facility electrification (HFE) promise concrete opportunities to target climate-health co-benefits, efforts to measure and maximize the health impacts of electrification have been limited by reliance on recall-based survey instruments for characterizing power challenges. Recent advances in digital monitoring tools and techniques, however, open new avenues for the design and tracking of development finance aimed at improving power challenges in low-resource health systems. We demonstrate the potential to track and scale data collection on both power quality and health outcomes by pairing cellular network-connected sensors with facility-level epidemiological indicators in the context of North Kivu, a uniquely challenging geography in Eastern Democratic Republic of the Congo. Our initial results suggest it is possible to quantify monthly reductions (deaths/facility) associated with each percentage improvement in aggregate power quality and reliability (**PQR**) tracked at facilities in a scalable manner with service utilization indicators of sufficient quality. We explore electricity-mortality tracking and reduction pathways related to changes in the availability of oxygen therapy for the treatment of hypoxemic, ischemic, anemic, and respiratory conditions in pediatric and internal medicine wards.

Keywords: health facility electrification, Internet of Things, humanitarian energy, epidemiology, Democratic Republic of the Congo.

1. Introduction

1.1. Health Facility Electrification

The COVID-19 pandemic reenergized interest in health facility electrification (HFE), driven by a focus on the temperature control requirements of vaccinal cold chains. It also highlighted limited evidence of progress amongst low- and middle-income countries, where ~1 billion people still rely on health facilities without high quality electricity [1].

To measure the outcomes of HFE, researchers have primarily relied on cross-sectional analyses of survey and administrative data at health facilities to explore equipment and health outcomes [2-14]. A limited number of reviews and meta-reviews of the extant literature also exist primarily providing estimations of the prevalence of power quality challenges at health facilities globally [15-18].

These studies have commonly relied on the definition of a power outage as two continuous hours without power in the past week, as recalled by a survey conducted with a health facility worker. To the best of the authors' knowledge, no study to date has used direct and continuous sensor-based monitoring of facility- and ward-level indicators of power quality and reliability, such as voltage, frequency, or grid-standard metrics like SAIDI/SAIFI and associated these with facility- and ward-levels health outcomes to inform public health investment or policy decisions [7].

1.2 Humanitarian Energy in the Democratic Republic of the Congo

The Democratic Republic of the Congo suffers from one of the lowest electrification rates on the planet [19], compounding the effects of one of the world's longest-running humanitarian crises. The 2022 resurgence of the armed M23 group in North Kivu Province precipitated a 20 year spike in violent conflict, displacing 1.3 million people in six months, increasing the total number of internally displaced people to six million. Already-anemic power infrastructures have been battered, with health facilities experiencing catastrophic blackouts amid ever-increasing healthcare needs directly caused by the conflict. The health and humanitarian implications of electrification in such conflict settings, though locally-specific, add an acute urgency to the imperative for innovative data collection efforts that can drive the most cost-effective interventions.

1.3 Research Questions

This paper is organized around three principal questions:

1. How are electricity challenges distributed across health facilities in North Kivu, specifically with respect to the frequency and duration of voltage, frequency, and outage anomalies?
2. Which of these electricity challenges have the greatest impact on health facility operations and patient outcomes?
3. How might electricity-related mortality and morbidity reductions be monitored rigorously and at scale?

2. MATERIAL AND METHODS

2.1. Data Collection

Through a formal partnership with the Provincial Health Department (Division Provincial de la Santé Nord Kivu, DPS-NK), we deployed power sensors at the electricity outlets of 25 hospitals and health centers between June-August 2022 (Figure 1.A-C). We then conducted structured and unstructured surveys with facility administrators, medical staff, and technicians, and engineers using WhatsApp and other phone-based communications (Figure 1.D). Lastly, we collected equipment usage, patient intake, and facility- and ward-level morbidity and mortality data for each of the 25 health facilities over 15 months of the electricity monitoring period (Figure 1.E).

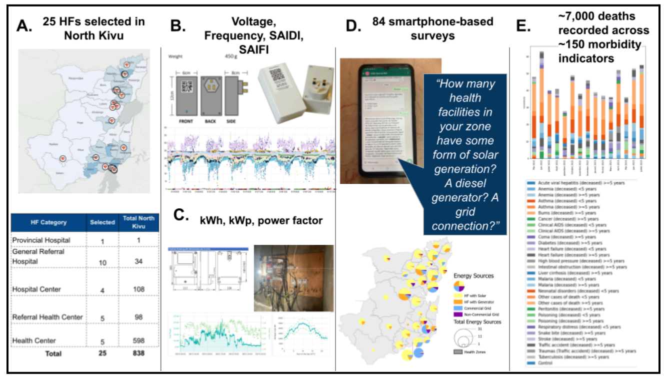

Figure 1: A) 25 (out of 838) health facilities selected for longitudinal tracking in consultation with the North Kivu Division Provincial de la Santé in July 2022; (B); 55 cloud-connected nLine PowerWatch sensors measuring electrical supply (voltage, frequency, outage duration and frequency at 2 min resolution) (C) 10 cloud-connected A2EI Hopmeters measuring electrical demand (kWh and kWp) at 1 minute resolution; (D) 84 smartphone-based surveys of health administrators, medical professionals, and energy technicians at the health facility and health zone level; (E) health facility-level service delivery indicators, including patient-throughput, morbidity and mortality for every health facility in the province, disaggregated over 15 months.

2.2. Calculation

For each facility we calculated a "reliability score", R, (eq. 1), a "quality score", Q, (eq. 2), and an aggregate "power quality and reliability aggregate score", PQR, (eq. 3).

R = average daily percentage of 'uptime' (Eq. 1)

The reliability score is calculated as the average count of daily interruptions times the average duration of daily interruptions. This generates an average percentage of time per day that all sensors at a given facility are reporting constant power supply. A two hour outage every day would thus equate to 91.7% uptime, while a single two hour outage on one day of one week would equate to a weekly uptime of 98.8%.

Q = average of percentage of time that both voltage and frequency are within nominal range (Eq. 2)

The quality score is the average percent of time per day that the voltage is within +/- 10% of nominal range (eg. 230 Volts) and the frequency is within +/- 5% of nominal range (eg. 50 Hz).

PQR score = (Q+R)/2 x 100 (Eq 3)

The PQR score is expressed as a simple unweighted average of the Reliability and Quality Score. The calculation is acknowledged as an initial attempt to quantify the landscape of PQR, and future work will interrogate outcome sensitivity to alternative weightings.

3. RESULTS

3.1 Power Quality and Reliability

We observed a wide range of power quality and reliability challenges across the 25 health facilities monitored. Figure 2 organizes the aggregate scores by lowest to highest (worst to best). Facilities across the sample experienced between 0 (zero power outages recorded over the entire period) to 2.42 outages per day, with the five most energy constrained facilities experiencing power outages of between 3.28-9.39 hours / day. Voltage and frequency excursions were particularly pronounced among remote hospital and reference health centers powered by older, hydropower grid systems.

3.2 Survey Results

Surveys of health facility staff at all levels indicate that the strongest linkages between electricity and mortality disproportionately cluster around services related to resuscitation in intensive care units, specifically with respect to the functioning of oxygen concentrator devices sensitive to poor power quality (Figure 3).

These electromechanical units, costing roughly 500 dollars each, require uninterrupted power to deliver oxygen-enriched air, ideally at the controllable flow rate of 5-50 liters per minute at 90-95.5% purity (vis-a-vis ambient air's ~21% oxygen concentration).

Frequency fluctuations are likely to considerably reduce the lifespan of compressors in concentrators, while voltage spikes damage microcontroller components. (Figure 4.) Risks of oxygen concentrator damage from AC frequency fluctuations are particularly notable for the extremes recorded among older hydroelectrically-powered facilities, with some facilities' power out of a 'safe' +/- 5% range of 50hz more than 80% of total time, potentially dependent on factors like local river flow conditions. Voltage stabilizers are hypothesized to themselves be susceptible to degradation due to such unregulated frequency. .

Health Facilities	CSR 1	HGR 1	CSR 2	CSR 3	CS1	HGR 2	CS2	CS3	HGR 3	CH1	CSR 4	HGR 4	CH2	CS4	CH3	HGR 5	HGR 6	HGR 7	CH4	HGR 8	HGR 9	HGR 10	HGR 11	HPN K	CS5
PQR Aggregate Score	28.2%	47.2%	66.1%	69.5%	75.0%	81.8%	87.6%	87.7%	88.5%	90.0%	91.2%	93.7%	95.4%	96.0%	96.4%	97.0%	97.3%	97.5%	97.6%	99.1%	99.2%	99.3%	99.9%	99.9%	100.0%
Quality Score (%)	12.2%	59.7%	38.2%	43.6%	82.3%	64.1%	92.6%	99.9%	93.5%	80.2%	90.0%	87.8%	92.8%	92.9%	92.8%	94.0%	95.0%	97.2%	95.5%	98.4%	98.5%	98.5%	99.9%	99.9%	100.0%
Voltage (% time in range)	0.122	0.765	0.571	0.052	0.646	0.418	0.854	0.999	0.903	0.606	0.915	0.807	0.869	0.857	0.891	0.884	0.934	0.991	0.912	0.972	0.999	1.000	1.000	0.999	1.000
Frequency (% time in range)	0.121	0.429	0.194	0.820	0.999	0.863	0.998	1.000	0.967	0.999	0.884	0.948	0.987	1.000	0.964	0.996	0.967	0.953	0.999	0.996	0.971	0.970	0.997	1.000	0.999
"Uptime" (Reliability Score %)	44.3%	34.7%	94.0%	95.4%	67.7%	99.4%	82.7%	75.4%	83.5%	99.8%	92.3%	99.7%	98.0%	99.2%	99.9%	99.9%	99.6%	97.9%	99.7%	99.8%	99.9%	100.0%	100.0%	99.9%	100.0%
Outages (count/day)	2.41	1.67	1.15	1.24	1.02	0.80	1.63	0.92	2.26	0.56	0.56	0.84	0.79	0.29	0.40	0.53	0.66	2.42	1.21	0.79	0.26	0.00	0.04	0.69	0.15
Outages (hours/day)	5.55	9.39	1.25	0.90	7.61	0.17	2.55	6.41	1.75	0.07	3.28	0.10	0.61	0.67	0.04	0.04	0.13	0.21	0.06	0.05	0.10	0.00	0.00	0.02	0.08

Figure 2: Aggregated and disaggregated power quality and reliability scores for 25 health facilities monitored at a sampling resolution of 2 minutes continuously over ~2 years.

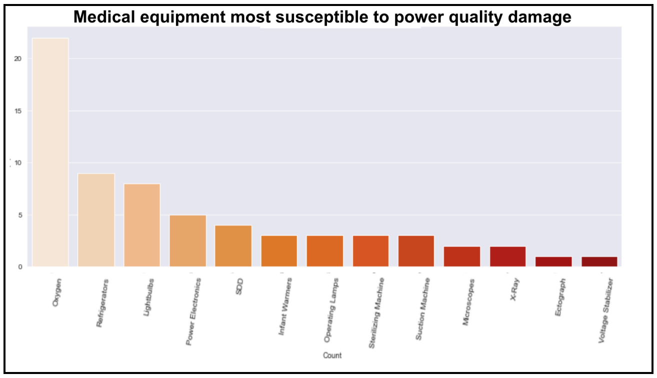

Figure 3: "In my Zone, the appliance that breaks down the most, likely due to power quality challenges is…" ranked order selection by facility technicians (n=24)

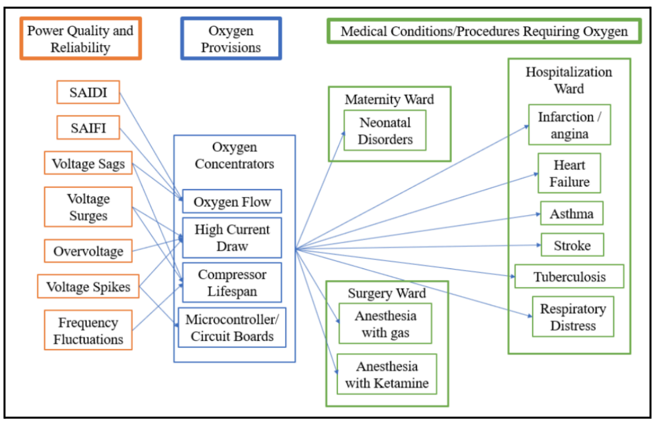

Figure 4: Conceptual mapping of power quality and reliability impacts on oxygen-related health outcomes

3.3. Linking electricity quality and reliability with health data

DPS data from the 25 health facilities account for 6,906 deaths tracked across 15 months at the 25 health facilities, including 352,321 new patient intakes. Five facilities account for 70% of deaths across over 100 service utilization, morbidity, and mortality indicators. The quality of service utilization data (for example, days of equipment non-functionality), however, appears too low for tractable analysis. Creative methods for developing high quality data on equipment failures and causes across wards is needed to provide more rigorous theoretical mapping for studying the value of various electricity-mortality reduction pathways.

3.4. Case Study

To highlight the variety of factors influencing electricity and health outcomes, we provide a short narrative description of oxygen delivery at a 290-bed facility in the peri-urban neighborhood of Ndosho in Goma, the capital of North Kivu.

Initially constructed in 2002, the private hospital was powered by SNEL, the national utility, but suffered from unpredictable and frequent cuts. Disconnecting itself in 2010, the facility powered itself autonomously through a 20kVA and 80 kVA generator managed by International Red Cross, its humanitarian partner, and a 5kWp/50kWh solar+battery pavilion array installed in 2015. In 2020, a second licensed grid operator reached the facility's neighborhood.

3.4.1. Power Supply: PQR score over the entire period monitored since 2022 is 90%, with daytime voltage sags dragging the facility's overall Quality score to an average of 80.23%. Power cuts average 0.56/day; average downtime of 4.2 minutes corresponding to 99.84% uptime reflects effective backup power response. The facility typically pays >$1,500/month for grid electricity and >$2,400/month for diesel fuel. Energy records (2020-2023) show that consumption of the latter is slowly but steadily decreasing over time as a share of total energy consumption.

3.4.2. Oxygen Concentration: Approximately 10 oxygen concentrators are used around the clock in the intensive care, resuscitation, surgery and neonatology wards of the hospital, amounting to approximately 10% of the facility's average daily consumption of 200-300kWh, and up to 20% of instantaneous draw during night-time load (Figure 5). Voltage stabilizers and uninterruptible power supplies are actively circulated throughout the facility with the devices as needed, though they are insufficient in number to protect all concentrators. Failure rates are reported monthly as 'days of non-functionality/month' for reanimation machines" (a category also including mechanical ventilators, defibrillators, etc.) but are reported inconsistently across months in the health system database.

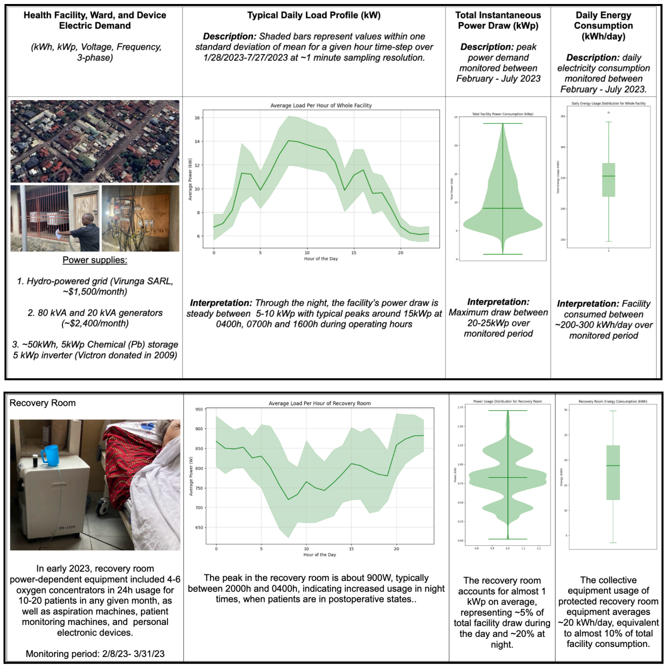

Figure 5: Energy consumption load profiles of total facility (three-phase) and intensive care unit (single phase) in instantaneous draw (kWp) and daily consumption (kWh).

In 2023, Goma's first oxygen-bottling plant was completed at a neighboring hospital, creating an economy for tanked medical oxygen refills. The health facility we focus on invested in the transition, and is currently recalculating the cost per hour of oxygenation charged to patients. Further research should explore reductions in failure associated with improvements in power quality and reliability, as well as track outcomes among patients with conditions requiring oxygen treatment compared to conditions not requiring oxygen treatment.

4. DISCUSSION

4.1. The need for comparable PQR metrics

A key contribution of this work is the collection and synthesis of high-resolution longitudinal data on power quality, reliability, and consumption across a diverse range of facility types and energy systems. The sensor deployment methodology is notable in its ability to produce comparable metrics on a number of distinct dimensions of electricity, whether supplied by a national grid, mini/micro/metro-grid, autonomous PV, thermal or hybrid system. These metrics offer the basis for constructing an easily-replicable tiered framework that offer development researchers, planners, and practitioners more rigorous quantification of power challenges than infrequently-administered recall-based surveys with limited econometric power.

Real-world longitudinal data on service utilization indicators like biomedical equipment usage is rare in the empirical literature, but particularly critical for understanding electricity-health pathways — as well as, from an implementation perspective, for improved accuracy of load-supply solar system dimensioning for off-grid and energy constrained systems. Given the early insights that electricity-oxygen mortality pathways may offer the highest opportunities for trackable patient outcomes, a stepped wedge randomized control trial design is proposed at hospitals (n=142) and reference health centers (n=98), where the majority of oxygen-related treatments and deaths take place. Such an experimental design, among the first of its kind for HFE [20], could additionally provide estimates on the cost-effectiveness of providing protection/backup devices to individual units versus, for example, redesigning oxygen devices entirely through solar direct-drive (e.g. DC-powered unit). The evidence base for these investment scenarios is all the more urgent against a global context in which up to 80% of medical equipment used in low-resource geographies has been designed for and subsequently donated from the West, where power conditions vary markedly from those found across the DRC and the African continent.

5. CONCLUSIONS

We analyzed live and longitudinal data from outlet-level power quality, reliability and consumption monitors, as well as remote surveys from key informants to frame an initial descriptive analysis of facility-level data from the provincial health database. The simultaneous collection of electrification data, service delivery and health outcomes from the facility unlocks the potential for a much more robust analysis of the linkages between power quality and health than has been possible in any previous studies on this topic. While further, more rigorous econometric analysis is yet to be conducted, our results suggest pathways between electricity, oxygen, and health outcomes offer tangible opportunities for experimental designs quantifying the health co-benefits of facility, ward, and device-level electrification technologies.

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