



# The power of health in the Democratic Republic of the Congo: Electricity quality and reliability in medical facilities of North Kivu Province

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## HIGHLIGHTS

- We collected power quality and reliability metrics at 25 facilities in North Kivu, eastern DRC over 29 months.
- Mean outage incidence across the sample was 0.67/day (min–max: 0–2.04), median outage duration: 2.01 h (0.03–10.9).
- 73.9 % of recorded voltage values fell within  $\pm 10$  % of nominal 230 V (min–max: 10.0–99.6 %) and 82.1 % of frequency values fell within  $\pm 5$  % of nominal 50 Hz (9.3–99.7 %).
- 16 out of the 25 facilities achieved “two nines” (99 %) of uptime. Facility uptime ranged from 46.7 % to 100 % (mean 93.2 %, median: 99.5 %, SD: 14.5).
- Outage incidence was overall lower in North Kivu than in comparable samples in Nigeria and Kenya, but outage durations were longer. Frequency quality was overall lower in North Kivu than in Nigeria and Kenya, but voltage quality was better than in Nigeria.
- Sensors offer significant improvements over survey recall in assessing the impact of energy poverty on healthcare outcomes.

## ABSTRACT

High-quality reliable electricity is essential for health service delivery, yet current World Health Organization (WHO) and World Bank Multi-Tier Framework (MTF) indicators rely on binary, recall-based survey metrics that fail to capture the incidence, duration, voltage or frequency of electricity in low- and middle-income country (LMIC) health facilities. Between 2022 and 2024, we deployed real-time, cellular-connected sensors in 25 health facilities across North Kivu Province, Democratic Republic of Congo (DRC), to continuously monitor outages, “uptime,” and the percentage of time electricity supply fell within  $\pm 10$  % of nominal voltage and  $\pm 5$  % of nominal frequency. Facilities experienced an average of 0.67 outages per day (min–max: 0–2.04), with a median duration of 2.01 h (0.03–10.9). Voltage compliance averaged 73.9 % (10.0–99.6 %) and frequency compliance 82.1 % (9.3–99.7 %). Sixteen facilities achieved  $\geq 99$  % uptime, the upper threshold mapping to the WHO’s current definition of reliable electricity. Uptime varied widely (46.7–100 %), underscoring the limitations of a reliable/not-reliable approach. Compared to those in Nigeria and Kenya, North Kivu facilities experienced fewer outages but substantially longer durations, with better voltage quality than Nigeria but worse frequency quality. By demonstrating the feasibility of continuous, auditable monitoring in a conflict-affected LMIC, this study shows how sensor-based metrics provide more sensitive and clinically relevant indicators of electricity performance than WHO and MTF frameworks. These findings support updating global electrification metrics to incorporate real-time uptime, voltage, and frequency indicators that better capture risks to biomedical equipment and patient outcomes.

## 1. Introduction

Electricity is a necessary input for the operations of nearly all biomedical equipment used to deliver routine and life-saving medical services in health facilities. Lighting, temperature control, X-ray and

ultrasound imaging, laboratory analyses, vaccine storage, sterilization, oxygen delivery — all depend on adequate and appropriate electrical supply. The COVID-19 pandemic reenergized interest in health facility electrification, driven in part by a focus on vaccine cold chains [1], and more recently, medical oxygen. It also highlighted the lack of healthcare facility electrification in low- and middle-income countries (LMICs),

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<https://doi.org/10.1016/j.apenergy.2025.126830>

Received 4 June 2025; Received in revised form 15 September 2025; Accepted 26 September 2025

Available online 9 October 2025

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## Nomenclature

### Power

HFE	Health Facility Electrification (activities tied to the provision and maintenance of electricity systems at facilities providing medical care)
IoT	Internet of Things (digital sensors and devices connected via wireless information networks for data collection/automation)
LMICs	Low- & Middle-Income Countries (World Bank classification based on Gross National Income per capita)
PQR	Power Quality & Reliability (metrics describing voltage, frequency, and outage characteristics)
UPS	Uninterruptible Power Supply (inverter-based energy storage and conditioning device)
SAIDI	System Average Interruption Duration Index (average outage duration per customer served)
SAIFI	System Average Interruption Frequency Index (average number of outages per customer served)

### Health

AS	Aire de Santé (Health Zone Area, smallest administrative unit covering several villages or neighborhoods)
CH	Centre Hospitalier (Hospital Center, private facility providing inpatient and surgical services, usually in urban areas)
CS	Centre de Santé (Health Center, primary care facility serving local communities)
CSR	Centre de Santé de Référence (Referral Health Center, intermediate rural facility offering both health center and hospital-level care)
DRC	Democratic Republic of the Congo (geographical study focus)
DPS	Division Provinciale de la Santé (Provincial Health Department, health system administration government agency)
FOSA	Formation Sanitaire (Health Facility, general term encompassing all levels of facilities)
HGR	Hôpital Général de Référence (General Referral Hospital, public facility providing specialized care at the top of the health zone pyramid)
MCZ	Médecin Chef de Zone (Zone Head Doctor, clinical and administrative lead of a health zone)
ZS	Zone de Santé (Health Zone, administrative unit typically covering ~100,000–200,000 people)

where a billion people are served by facilities with no or low-quality electricity [2].

When power grids fail, outages require hospital staff to manually switch the facility's circuits to secondary power sources, typically diesel generators, as quickly as possible. Diesel generators account for up to 20 % of African countries' available electricity capacity, and their use as a coping strategy against grid unreliability comes with significant financial, environmental, and human consequences [3]. While there is strong suggestive causal evidence of negative effects of outages on economic growth, official data on African electric grid performance — including utility-standard indices expressing how often customers in a zone experience power interruptions (SAIFI) and how long interruptions last (SAIDI) — often rely on electricity utility provider self-reporting or infrequently performed surveys rather than continuous telemetric readings as in developed economies [46,47].

While most studies on electricity in health facilities primarily or only examine access — the presence or absence of electricity [4] — the ability to “derive benefits” from electricity access [5] largely depends on power quality and reliability (PQR) [6]. Power interruptions or deviations in voltage or frequency can render unusable many of the ~10,000 biomedical devices critical for prevention, diagnosis, treatment, and rehabilitation. [7].

In the health facility electrification scholarship, electricity access is typically categorized as “always available” if no interruptions lasting longer than two continuous hours in the week prior to the survey were recalled by the health facility respondent at the time of the interview, in line with the WHO's Standard Provision Assessment service utilization assessment toolkit (“During the past 7 days, was electricity (excluding any back-up generator) available during the times when the facility was open for services, or was it ever interrupted for more than 2 hours at a time?” Special instructions: Consider electricity to be always available if interrupted for less than 2 h at a time.) Between 2015 and 2022, WHO surveys collected this information at a nationally representative scale from only eight countries in Sub Saharan Africa [2].

At this two hour threshold definition, ~40 % of facilities in Africa have electricity that is “always available” while ~60 % experience “unreliable” electricity, an estimate that has decreased only slightly since 2013 [8]. Unreliable power at health facilities has been linked with increased all-cause mortality rates [9,10], decreased prevalence of in-facility birth [11], and reduced staff satisfaction [12]. These results would likely be stronger if the indicators for health facility electricity access were more sensitive and specific. Indeed, the WHO and other health practitioners have explicitly called for improved metrics for quantifying the quality and reliability of electricity in health facilities [2,13]. The timing and duration of outages at health facilities — including brief or momentary power cuts — may have important consequences for patient outcomes, but these aspects are difficult for respondents to accurately recall [14].

Beyond reliability, power quality also affects healthcare delivery. Biomedical devices and power systems are both designed around nationally determined power quality standards (typically 220–240 V and 50 hertz in Europe, Africa, and parts of Asia and 120 V and 60 hertz in the United States). Voltage and frequency deviations may be nearly impossible to notice or recall given that these phenomena occur at the sub-second level. In one of the only empirical studies characterizing biomedical equipment failures in LMICs — a 2007 study spanning 10 countries and 33 hospitals in which 975 broken biomedical devices were analyzed — power was identified as the primary cause of equipment failure, but the aspect of power that caused the failures (e.g. voltage, frequency, momentary or prolonged cuts) was not identified [15]. Biomedical equipments' sensitivity to PQR drives the need to demarcate facility circuits and electrical outlets by their backup and protection needs, in order of sensitivity: “secured”, “non-secured”, and “non-critical” [45].

Recent sensor technology innovations have enabled substantial improvements in the precision of health facility electrification data that can help bridge the gap between power and health outcomes. A Sierra Leone study, for example, measured an average of 3 outages per day, each with a median duration of 3 h, and lower average voltage levels in non-hospitals compared to hospitals [16]. Biomedical-focused literature has increasingly leveraged remote monitoring to evaluate LMIC health setting infrastructure, while open-source electric reliability monitoring initiatives have emerged, such as Prayas Energy (Pune, India), eHealth Africa (Abuja, Nigeria), and nLine (Berkeley, USA).

There remains considerable uncertainty regarding which aspects of PQR matter to patient outcomes across the diversity of operational contexts found in LMICs, which include active conflict, post-conflict, and other humanitarian settings. A study on oxygen availability in rural Kenya ( $n = 11$  facilities, 10 months) recorded an average of 1 outage per day [17] and mortality rates three times higher among facilities monitored with outages longer than 30 min than those without,



although these results were not statistically significant. More systematically collected information on power and health indicators is thus likely needed to provide causal insight into how improved electricity can lead to improved health outcomes like patient survivability or mortality reduction.

Unlike prior work that has relied on WHO surveys or the World Bank's Multi-Tier Framework (MTF)—both of which emphasize respondent recall — this study presents one of the first datasets produced by high-resolution sensor data to measure power quality and reliability in health facilities across a conflict-affected LMIC. As a first step to better understanding the link between healthcare facility power quality and reliability and health outcomes, we asked the following research questions: 1) How often do power-stressed health facilities experience outages, and how long do they typically last? 2) What proportion of power supplied at health facilities exceeds nominal ranges for voltage and frequency? 3) How are the impacts of PQR differentially experienced across facility types, power sources, and geographic contexts?

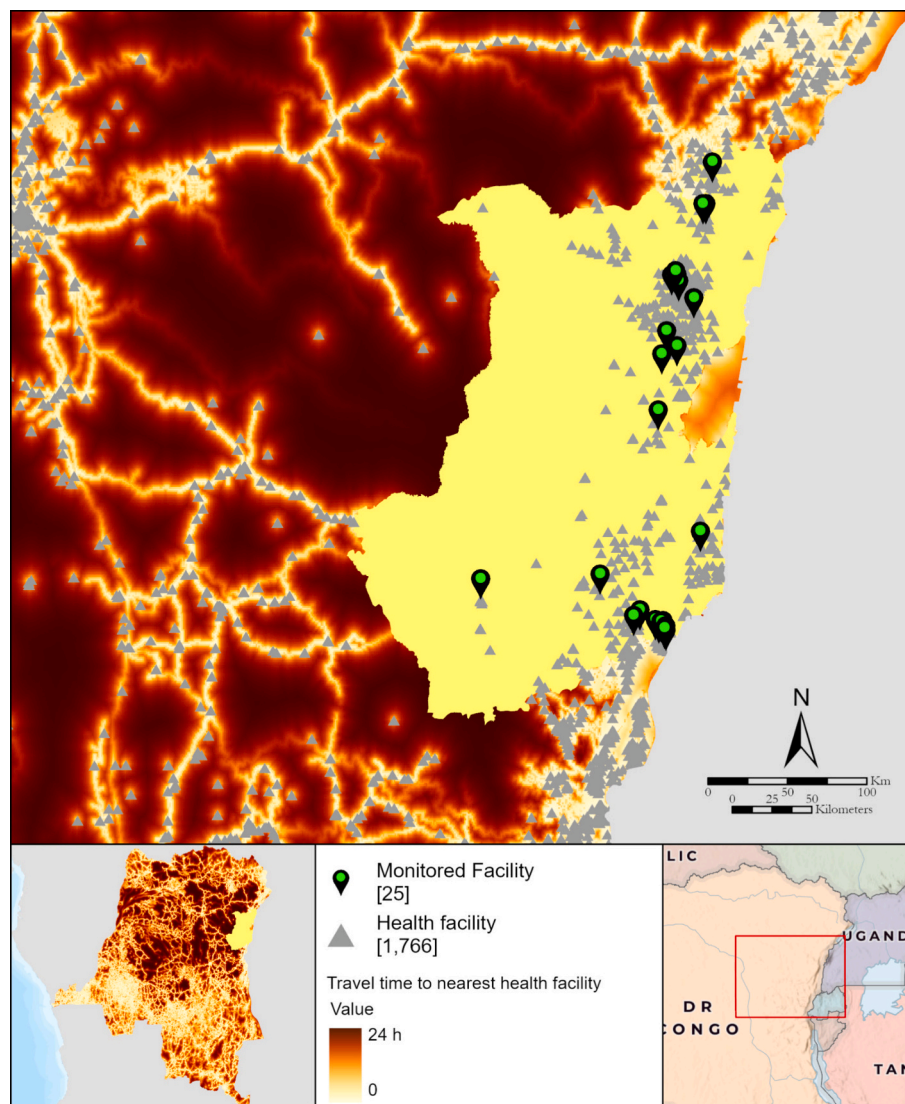
## 2. Methods

We deployed sensors at health facility electricity outlets; surveyed health system administrators, doctors, and technicians; and (when/where feasible) performed in-situ observation of electricity usage in healthcare facilities over 29 months.

### 2.1. Study site and sample selection

The study was conducted in the North Kivu province in eastern Democratic Republic of the Congo (DRC, Fig. 1). North Kivu has experienced ongoing violent conflict for over 30 years. We selected North Kivu because most scholarship on African power systems has been conducted in Anglophone and relatively peaceful settings [18], despite the fact that the DRC hosts one of Africa's largest under-electrified populations, with health impacts disproportionately felt by women and children [19–21].

North Kivu, unlike most other African regions experiencing long-term conflict and other provinces in the DRC, hosts a wide range of



**Fig. 1.** 25 health facilities selected for monitoring in North Kivu, DRC.

**Bottom left:** inset of the DRC with North Kivu colored in yellow. Travel time by walking to the nearest health facility (outside North Kivu) is colored red (dark red = longer travel time to nearest health facility), from [27]. **Top:** North Kivu province colored in yellow. Pins denote facilities selected for monitoring. Gray triangles represent non-monitored facilities, from [28]. **Bottom right:** North Kivu's regional borders with Rwanda and Uganda. Credits: ESRI, TomTom, Garmin, FAO, NOAA, USGS.



power suppliers [22]. Five commercial electricity operators are federally licensed to offer electricity services, including the national grid provider SNEL (Société Nationale d'Electricité) and four commercial distributors (Virunga, SOCODE, Nuru, Energies du Nord Kivu), alongside numerous locally or community-managed run-of-river hydroelectric generation and distribution systems. These are often referred to as microgrids or “second generation minigrids” [23–26].

We selected 25 health facilities (Fig. 1 and Table 1) for longitudinal observation in collaboration with the Provincial Health Department (Division Provinciale de la Santé Nord Kivu, DPS-NK). Facilities with the largest catchment populations and with some form of electricity to monitor were selected from the three largest cities in North Kivu (Goma, Beni, and Butembo) and their catchment areas, as well as from large remote population centers (e.g. hospitals more than 3 h by road from the nearest city). These facilities thus likely overall represent better-provisioned facilities with relatively high patient counts for their facility type.

The sample included facilities in communities experiencing both historical and/or active organized conflict [29]. Our sample included the one provincial hospital (Hôpital Provincial, “HP”); 11 of the province’s 34 General Referral Hospitals (Hôpital Général de Référence, “HGR”); four private hospitals (Centre Hospitalier, “CH”); four Referral Health Centers (Centre de Santé de Référence, “CSR”); and five Health Posts (Postes de Santé) given the limited electricity supply and biomedical equipment at these small facilities. Health Centers in our sample were predominantly located in urban and peri-urban areas, as most remote ones had little or no electricity sources to monitor for the study.

**Table 1**  
Description of facilities (excluding health posts) in the health referral system of North Kivu, DRC, as of 2022.

Health facility category	Description	Total in North Kivu	Number of facilities selected
Provincial Hospital (Hôpital Provincial, HP)	Top of referral pyramid; 1 per province	1	1 (HP)
General Referral Hospital (Hôpital Général de Référence, HGR)	Offer standard services requiring power (surgery, imaging, diagnostics, etc.); 1 per Health Zone	34	11 (HGR 1-HGR11)
Hospital Center (Centre Hospitalier, CH)	Same services as HGRs but often specialized (eg gynecology, dentistry). Privately funded and operated, often by faith-based groups	108	4 (CH1-CH4)
Referral Health Center (Centre de Santé de Référence, CSR)	“Remote hospital,” managed by a resident doctor; offer limited hospital services (including surgery & intensive care) in isolated areas	98	4 (CSR1 - CSR4)
Health Center (Centre de Santé, CS)	Managed by resident nurse who performs vaccinations and provides consultative services; typically includes a pharmacy	598	5 (CS1-CS5)
Total in North Kivu		838	25

Note: The smallest administrative health unit is an Aire de Santé, which is served by a health center (CS). When a case requires more medical care than a health center can provide, the patient is referred up the referral pyramid to the appropriate facility (CSR or HGR, the latter of which is responsible for one of the Province’s 34 Health Zones). HP is the provincial hospital responsible for cases referred to the top of the referral pyramid for all of North Kivu.

## 2.2. Data collection

### 2.2.1. Surveys

In 2022 and 2023, we conducted a survey targeting head doctors from 34 health zones, head doctors of selected facilities and, where available, their electricity technician (SI A.1–2). These surveys included questions on power sources used at each facility, biomedical equipment usage, failure rates and causes, and facility-specific morbidity context. Respondents received a Whatsapp message with a link initiating a chat with a survey chatbot [30], which elicits responses question-by-question in a manner similar to natural conversation. Response formats included ranked-choice selection questions, multiple choice, long-form typed responses, and open-ended voice-notes. Surveys were designed to take approximately 20 min, and could also be completed in multiple sessions rather than all at once, to accommodate healthcare workers who were on duty. Respondents received a mobile money transfer between 5 and 10 USD upon completion of the survey to compensate them for their time and data costs. We received responses from 100 % of Zone Head Doctors (34/34) and 96 % of health facility head doctors/nurses and technicians (24/25).

### 2.2.2. Sensors

To assess PQR at healthcare facilities, we installed continuous real-time PowerWatch sensors (nLine.io; Berkeley, CA, USA) [31,32]. These “Internet of Things” (IOT) devices provide high-resolution detail and unique insights into site-level power phenomena, which are typically invisible even in industrialized economies [33,34]. We deployed two sensors at outlets in different wards of the 25 health facilities selected between May and August 2022. Each sensor, equipped with four hours of rechargeable internal energy autonomy, averages PQR data over a two-minute interval. Using an embedded multi-telecom network SIM card, each sensor reports high-precision voltage, frequency, and outage readings to a cloud-based data warehouse. Outage incidence and duration are recorded when two or more sensors monitoring a given power source simultaneously report power failure, filtering for “fake” outages (e.g. if a cleaning personnel unplugs a sensor). Data reliability is auditable with approximately five minute latency via commercial front-end data platform provider ([www.grafana.com](http://www.grafana.com)). In this paper, we present sensor data monitoring the period to October 2024, for a total coverage of approximately 29 months (2.4 years).

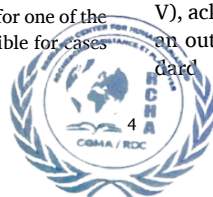
## 2.3. Data analysis

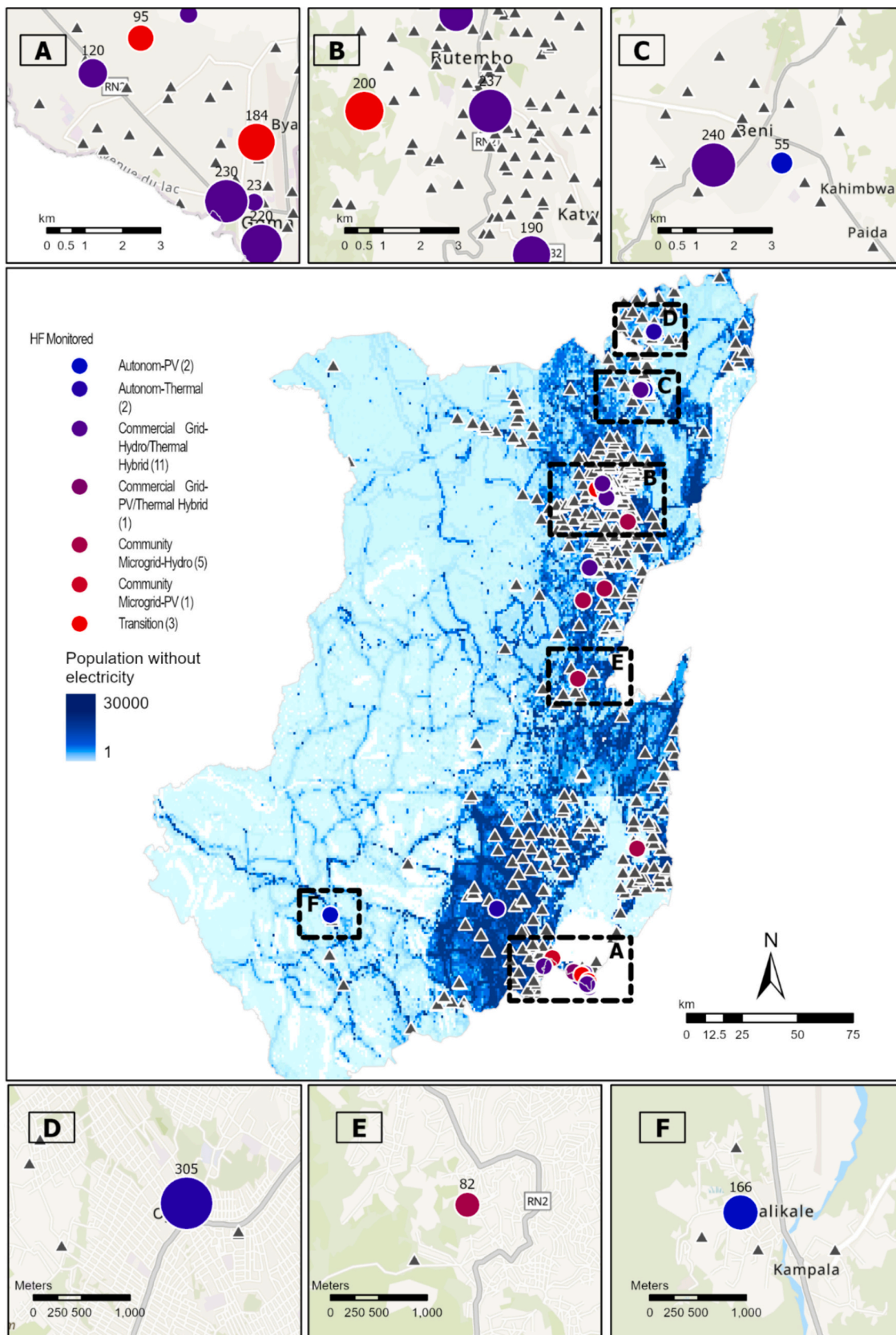
### 2.3.1. Surveys

Once the respondents’ audio and written responses were transcribed, the data were systematically coded using both a priori themes and emergent themes that arose during the analysis process. Thematic analysis was then conducted to identify patterns, trends, and key insights within the data. This process involved grouping responses into relevant categories and examining them to draw meaningful conclusions related to the power sources, biomedical equipment usage, failures, and the unique morbidity context of each facility.

### 2.3.2. Sensors

Based on the sensor data, we calculated descriptive statistics of PQR, including outage incidence per day and outage duration per day. These would alternatively be referred to as system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) in large-scale power systems analysis, but in this study we perform single-site, not grid-system, analysis. In our study, an outage is defined as when two sensors simultaneously report a zero or near-zero voltage state. The threshold used was 23 Volts (10 % of nominal 230 V), acknowledging that the distinction between a low-voltage event and an outage instance lies along a spectrum bifurcated by no single standard across studies. Additionally, we calculated “uptime,” the





**Fig. 2.** Monitored facilities across North Kivu, by power type. **Center:** Population without electricity in North Kivu colored in dark blue, based on satellite imagery analysis from [27]. Circles represent monitored health facilities, color-coded by health facility type and gray triangles are non-monitored facilities from [28]. **Top row:** insets of facilities in urban zones of Goma (A), Butembo (B), and Beni (C). **Bottom row:** insets in remote zones of Oicha (D), Kirumba (E), and Walikale (F). Size of monitored facilities in insets scaled to number of beds. Credits: RLMUA, ESRI, OpenStreetMaps contributors, TomTom, Garmin, METI/NASA.



percentage of total time a power system is delivering electricity of any quality. We express uptime as the mean daily proportion of time without an outage, calculated as a product of mean daily outage incidence and median daily outage duration on days with one or more outages.

We calculate the amount of time that voltage was recorded within  $\pm 10\%$  of the nominal value. While nominal voltage in the DRC is set by the national grid at 220 V, we calculated nominal thresholds around 230 V in line with the International Electric Commission's voltage standard harmonization efforts, and because most medical devices used in the DRC are imported from Europe where nominal thresholds can be 220, 230, or 240 V. Given the lack of consensus on universally appropriate frequency tolerance ranges, we calculated the amount of time per day that frequency remained within various ranges:  $\pm 10\%$  (45–55 Hz),  $\pm 5\%$  (47.5–52.5 Hz),  $\pm 1\%$  (49.5–50.5 Hz) and  $\pm 0.1\%$  (49.95–50.05 Hz) of the nominal value of 50 Hz (see SI A.5–6 for further discussion). We present data for each facility, facility type, and power system type. Given the small number of facilities in each group, we did not expect our differences in power quality and reliability by facility type to be statistically significant and report them in SI D. We also include in the SI information on each facility's type, power source, and catchment context.

### 3. Results

#### 3.1. Overview of health facility power in north Kivu

Of 838 HGRs, CHs, CSRs, and CSs in North Kivu enumerated in surveys with Zone Head Doctors (Médecins Chefs de Zones, MCZ), approximately half had no electricity. 440 facilities (52 %) had photovoltaic solar systems as either a primary or secondary power source, 104 (12 %) used generators, 92 (11 %) were connected to a federally-licensed grid provider, and 25 (3 %) were powered by locally- or community-managed power systems. Further context on surveys, including questionnaires and selected results from Health Zone head doctors, can be found in SI A.1–2.

Of the 25 facilities selected for power assessment, General Referral Hospitals (HGRs) were built between the 1920s and 1960s; most other facilities were constructed in the 1980s and 1990s. Private hospitals (CHs) had the highest staff-bed ratio across facility types, while Referral Health Centers (CSRs) had the lowest (Table 2).

12 of the monitored facilities were powered by a licensed electricity provider at the beginning of the study. Six were connected to hydro-power or solar "community microgrid" systems and seven facilities were autonomously powered, relying either primarily on their own diesel or solar generation for electricity. Three of the autonomously powered facilities became connected to a licensed electricity grid provider at some point in the study (Fig. 2). This diversity of power sources, atypical even among African geographies, provides further evidence that increasing electricity access in North Kivu and across the DRC will require technical and financial strategies tailored to its unique context.

All monitored public and private hospitals had at least one working backup generator between 7 and 65 kVA, most of which consumed between \$300–\$750 monthly in fuel. All Referral Health Centers had

**Table 2**  
Basic characteristics of 25 monitored health facilities.

Health facility category	n	Year of Construction Mean (SD)	Staff Mean (SD)	Beds Mean (SD)	Staff-to-Bed Ratio Mean (SD)
HP	1	1986 (–)	229 (–)	230 (–)	0.99 (–)
HGR	11	1947 (25)	172 (84)	216 (88)	0.8 (0.3)
CH	4	1991 (21)	285 (15)	194 (54)	1.5 (0.3)
CSR	4	1987 (12)	37 (8)	79 (14)	0.5 (0.1)
CS	5	1996 (14)	21 (12)	28 (17)	0.8 (0.3)

small, portable generators between 2 and 5 kVA used to power specific critical equipment, wards, or services, either directly or through in-facility wiring to wall outlets. Four Health Centers had a grid connection — three with commercial hydro-grid connections, and another connected to a solar microgrid. The fifth selected for the study was autonomously powered by multiple sets of rooftop PV (Table 3).

#### 3.2. Power quality and reliability

Table 4 presents summary statistics of the distribution of reliability (outage incidence, duration and uptime) and quality (voltage and frequency) aggregated over the sample, by facility type, and by power source. The Provincial Hospital's PQR was among the best in sample, though its outage incidence was slightly worse than the total sample mean, at 0.69 outages / day. Public hospitals had equal or worse PQR than private hospitals and slightly more time within the nominal voltage range; both facility types at the top of the referral pyramid had better PQR than Referral Health Centers and Health Centers at its bottom. Referral Health Centers had the overall worst PQR, with the lowest average uptime at 85.59 %. When power sources were compared by type of generation, PV generally performed best across all PQR indicators. For example, facilities connected to commercial grids powered by PV with a diesel generator backup had better PQR than those connected to commercial grids powered by hydro with diesel generator backup, and facilities autonomously powered by PV had better PQR than those autonomously powered by diesel generation.

##### 3.2.1. Outage incidence

Mean daily outage incidence over the entire sample was 0.67 outages/day ( $\sim 5$  outages/week), ranging from 0.0 to 2.05 / day across

**Table 3**  
Primary power sources and electricity providers serving the health facilities.

Electricity Provider	Primary Power Source	Generation Capacity / Coverage	HFs connected to this power system
Government/ Commercial Grid ("SNEL")	Hydro	$\sim 6$ MW from Ruzizi plant in Bukavu.	HP, HGR3, CH3, CS3
Commercial Grid ("Virunga")	Hydro	$\sim 15$ MW across two hydro plants and non-interconnected grids serving Goma & Lubero	HGR6, CH1, CS4
Commercial Retail Grid (SOCODE)	Hydro	0 MW ( $\sim 3$ MW purchased from Virunga and redistributed to commercial and residential customers in Goma)	HGR10, CH3, CS3
Commercial Grid ("Energies du Nord Kivu")	Hydro	$\sim 1.8$ MW generated and distributed to commercial and household connections in Beni and Butembo	HGR1, HGR2, HGR4, CH2, CH4
Community microgrid	Hydro, Solar	$\sim 8$ –600 kW, powering households, public, and commercial connections across tertiary cities like Lubero, Kirumba, or Kyondo	HGR9, HGR5, CSR1, CSR2, CSR3, CS5
Commercial Grid ("Nuru")	Solar	$\sim 1.3$ MW generated and distributed to household and commercial connections in peri-urban Goma.	CSR4, CS1
Autonomous microgrid ("off-grid" / facility-level power)	Solar, Diesel, Hydro	$\sim 5$ –100 kW, powering the different parts of health facilities' campus	HGR11, HGR8, HGR7, CS2

Note: Total facilities by power source do not add up to 25 because some facilities' primary power source/system transitioned during the monitoring period, and because some facilities had multiple connection types.



**Table 4**  
Electrical power quality and reliability metrics by facility type and power source type.

	n	Reliability		Quality		
		Daily outage incidence (count/day) mean (sd) [min, max]	Outage duration (hours/day, mean of medians excluding days with zero outages) (sd) [min, max]	Uptime (%) mean (sd) [min, max]	% time voltage was within $\pm 10\%$ of 230 V mean (sd) [min, max]	% time frequency was within $\pm 5\%$ of 50 Hz mean (sd) [min, max]
All facilities	25	0.67 outages / day	2.01 h / day	93.20 %	73.89 %	82.07 %
Facility Type						
HP	1	0.69 (–)	0.04 (–)	99.90 (–) 94.65 (15.91) [46.72, 100.00]	99.56 (–)	99.68 (–)
HGR	11	0.63 (0.60) [0.00, 2.05]	1.17 (3.10) [0.00, 10.45]	99.67 (0.23) [99.36, 99.91]	79.88 (24.48) [26.62, 98.84]	85.99 (23.91) [14.96, 96.96]
CH	4	0.57 (0.36) [0.22, 1.06]	0.16 (0.13) [0.07, 0.35]	85.59 (18.93) [57.57, 99.21]	79.21 (17.11) [53.88, 91.17]	95.00 (3.11) [92.15, 98.19]
CSR	4	0.97 (0.61) [0.25, 1.66]	3.80 (3.55) [0.25, 7.48]	89.56 (15.02) [64.66, 99.95]	39.82 (26.66) [9.99, 71.36]	44.39 (36.60) [9.31, 81.50]
Power Source						
CS	5	0.56 (0.54) [0.09, 1.38]	3.91 (4.85) [0.13, 10.94]	99.97 (0.04) [99.95, 100.00]	70.26 (20.92) [38.77, 95.03]	80.44 (16.65) [61.18, 95.76]
Autonomous - PV	2	0.05 (0.06) [0.00, 0.09]	0.07 (0.09) [0.00, 0.13]	73.36 (37.67) [46.72, 100.00]	96.94 (2.69) [95.03, 98.84]	95.55 (0.97) [94.86, 96.23]
Autonomous - Thermal	2	0.63 (0.85) [0.03, 1.22]	5.24 (7.37) [0.02, 10.45]	96.13 (10.47) [64.66, 99.92]	60.31 (47.64) [26.62, 94.00]	54.36 (55.72) [14.96, 93.76]
Commercial Grid - Hydro/ Thermal Hybrid	11	0.65 (0.35) [0.19, 1.38]	1.27 (3.23) [0.04, 10.94]	99.92	74.42 (21.37) [38.77, 99.56]	90.08 (10.89) [61.18, 99.68]
Commercial Grid - PV/ Thermal Hybrid	1	0.10 (–)	0.99 (–)	99.57 (–) 89.69 (18.15) [57.57, 99.89]	80.32 (–)	95.76 (–)
Community Grid - Hydro	5	1.24 (0.64) [0.48, 2.05]	1.59 (2.59) [0.06, 6.14]	86.16 (–) 97.21 (4.22) [92.34, 99.91]	56.23 (39.51) [9.99, 97.74]	59.33 (42.67) [9.31, 96.96]
Community Grid - PV	1	0.47 (–)	7.04 (–)	82.32 (10.06) [71.36, 91.15]	64.17 (–)	64.24 (–)
Transition	3	0.45 (0.39) [0.22, 0.90]	2.58 (4.24) [0.10, 7.48]			86.00 (14.05) [69.93, 95.94]

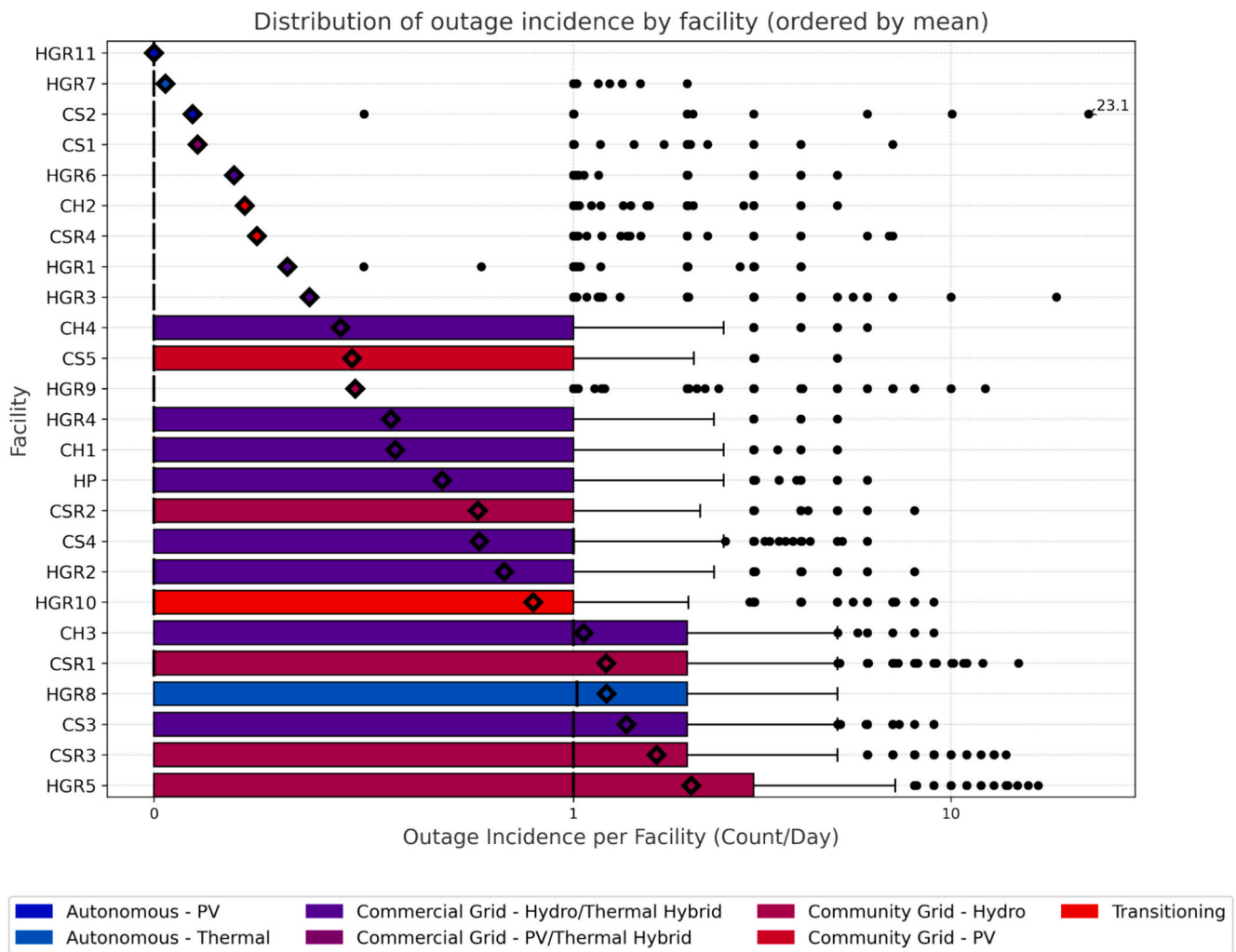
facilities (Fig. 3). Private hospitals experienced lower outage incidence than public ones (HGRs and HP); Referral Health Centers experienced almost double the outage incidence of the Health Centers (Table 4). Two facilities in our sample experienced zero or near-zero outages over the monitored period; both of these (HGR11 and HGR7) were supported by Doctors Without Borders (Médecins Sans Frontières, MSF). The “bottom three” facilities in terms of highest outage incidence included a public hospital, a Referral Health Center and a Health Center with 25th and 75th percentile values between 2 – 10 outages / day. See Section 3.3 and SI B1–4 for ordering and groupings by referral pyramid hierarchy and power source. High outage incidence primarily implies the need for uninterruptible power supplies (UPS) to mitigate the potentially significant impacts of even brief cuts, for example by spoiling laboratory test samples.

### 3.2.2. Outage duration

The mean of facilities’ median outage duration across the sample (calculated excluding days with no power cuts to capture typical duration of outages when they did occur) was 2.01 h, ranging from 0.03 h to

10.9 h per day (Fig. 4). Aside from the two MSF facilities, which had median outage duration of 0 and 0.03 h respectively, the Provincial Hospital had the lowest outage duration at 0.03 h (1.8 min) without power per day. It was the only facility with a functional auto-start backup generator (a system that activates backup generators and switches the entire facility over to them when a power outage from the grid is detected); several facilities reported that their generators had “auto-start” capabilities but this function no longer worked. Private hospitals typically experienced much shorter outages (0.16 h) than public ones (1.17 h), Referral Health Centers (3.80 h), and Health Centers (3.91 h). The facilities with the longest duration outages were powered by hydro minigrid stations or solar systems with depolarized lead-acid batteries, or had affordability limitations related to fuel-based or pre-paid meter-based electricity. High outage duration can compromise cold-chain integrity and oxygen therapy, and implies the need for additional energy storage or generation, for instance through solar, batteries or diesel backup generators.





**Fig. 3.** Distribution of outage incidence (count/day) from 25 health facilities in North Kivu, DRC Facilities, anonymized along their facility type designation (HP = Provincial Hospital, HGR = General Referral Hospital, CH = Private Hospital, CSR = Referral Health Center, CS = Health Center), are ordered by mean (indicated by the diamond) and are color-coded by their primary power source, though they may have multiple power sources.

### 3.2.3. Uptime

Total mean uptime across the sample was 93 %; the two MSF facilities achieved “four+9 s” of uptime (99.99 % and 100 %) over the monitored period. If reliable electricity is considered to be less than two hours of outage per week (98.8 % uptime), 16 of the 25 facilities experienced “reliable” electricity. Four facilities failed to achieve 90 % uptime (‘one nine’). Across the groups, only private hospitals and the Provincial Hospital had mean uptime >99 %; across power supply types, only PV-commercial grids and autonomous PV facilities achieved mean uptime >99 % (Table 3). The facility with the lowest uptime (<50 %) was HGR8, which was autonomously powered through generator and fuel rationing in an area with no commercial or community grid. Uptime by facility is provided in SI A.3. Uptime can be used as a direct proxy for reliability.

### 3.2.4. Voltage

The mean proportion of time voltage was within  $\pm 10$  % of 230 V in our sample was 74 % (min  $\sim 10$  %, max  $\sim 100$  %). Undervoltage represented the vast majority of voltage excursions across the sample; overvoltage was concentrated in Referral Health Centers powered by community micro-hydro grids (Table 4). In these facilities, the mean proportion of time voltage was maintained within range was <50 %. Significant proportions of time were recorded at near-zero voltage levels at HGR8, CSR4, CS5, CSR2, CSR4, CS3, CSR3, and CSR1, highlighting

the spectrum between low-voltage events and power cuts (Fig. 5). Poor voltage implies the need for voltage stabilizers or other power conditioning devices.

### 3.2.5. AC frequency

We measured the proportion of time facilities were within  $\pm 10$  %, 5 %, 1 % and 0.1 % of 50 Hz (SI A.6). At these thresholds, the proportion of total time facilities’ electric AC frequency was within range was 84.94 %, 82.07 %, 65.34 % and 18.28 %, respectively. Frequency deviations were concentrated in CSRs (Table 3) and facilities powered by older (>10 years) and smaller (<100 kW) micro-hydro facilities, among which we observed chronic under-frequency (between 40 and 50 Hz), over-frequency (between 65 and 70 Hz), and frequencies between 50 or 60 Hz nominal standards (eg. 55 Hz). At CSR3, frequency was within nominal range less than half the time for every threshold applied (Fig. 6). Poor frequency has the potential to interfere with equipment including voltage stabilizers. Depending on the severity of its impact on equipment, implies the need for power conditioning equipment or power source stabilization (e.g. greater governor control for hydro-based power sources).

Voltage and frequency issues highlight that ‘electrified’ facilities may still be unsafe for sensitive biomedical equipment, making protection circuits and power quality as important as access itself.



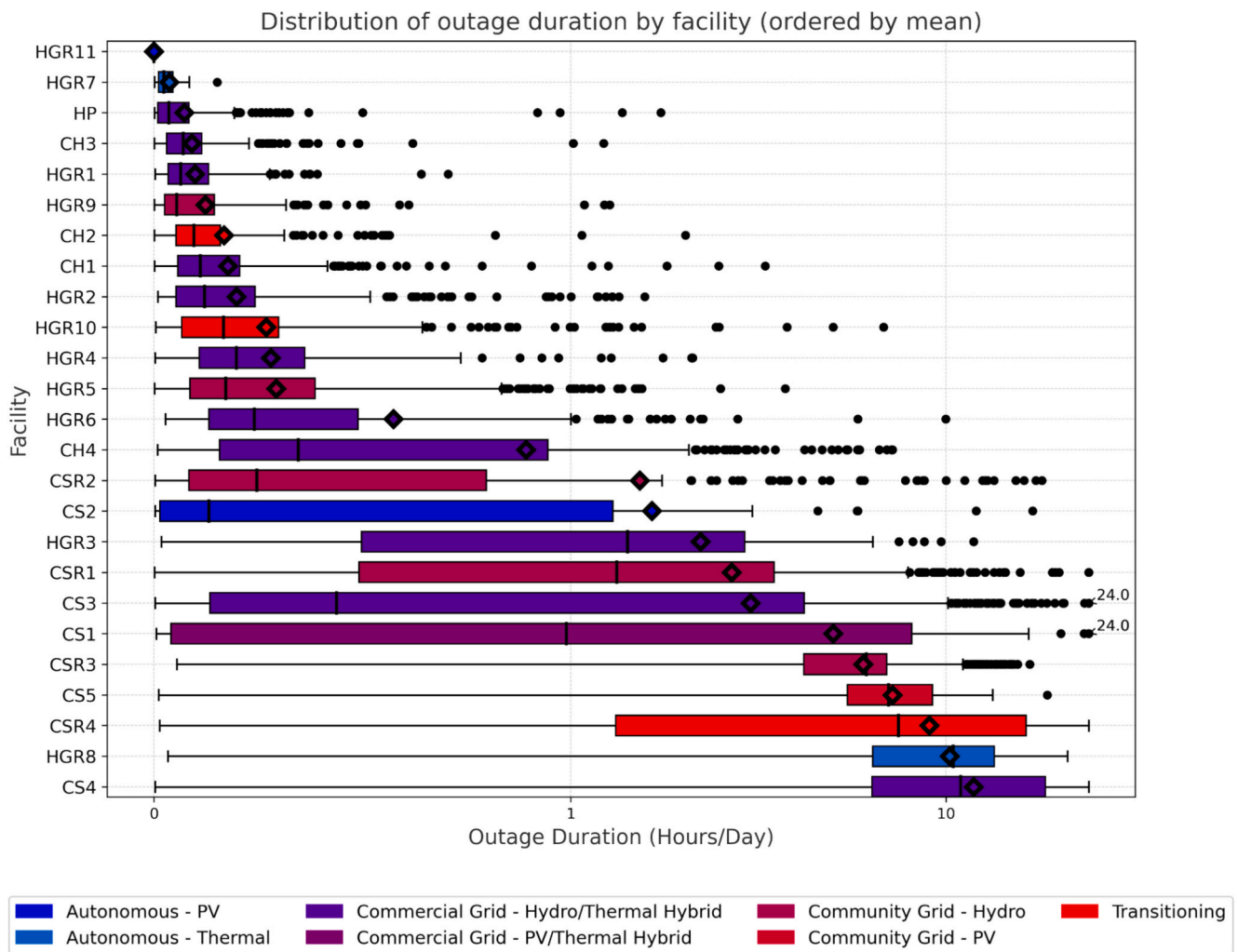


Fig. 4. Distribution of outage durations (hours/day) from 25 health facilities in North Kivu, DRC Facilities, anonymized along their facility type designation (HP = Provincial Hospital, HGR = General Referral Hospital, CH = Private Hospital, CSR = Referral Health Center, CS = Health Center), are ordered by mean (indicated by the diamond) and are color-coded by their primary power source, though they may have multiple power sources.

### 3.3. Power quality and reliability across the North Kivu health facility pyramid

Health facilities in North Kivu exhibited distinct energy profiles shaped by their role in the referral system, geography (urban centrality/remoteness), and the nature of the power system supporting the facility. PQR is aggregated by facility type in Fig. 7.

#### 3.3.1. Provincial hospital (HP)

North Kivu’s Provincial Hospital, the top of the health referral system, was characterized by high quality power in terms of voltage and frequency thanks to its dedicated step-down transformer connection from national utility grid (SNEL). Though it experienced relatively high incidence of interruptions, it had high overall uptime due to its functioning auto-start generator.

#### 3.3.2. General referral hospitals (HGR)

The Province’s 34 General Referral Hospitals serve as the backbone of healthcare delivery, offering secondary-level care to large populations. HGRs are typically located at the center of urban agglomerations. In North Kivu, most were connected to commercial grid providers, supplemented with diesel generators and solar backup systems. While uptime between 99 and 99.9 % (“2–3 nines”) was typical, we observed peak-hour voltage sags, aging infrastructure, and affordability concerns.

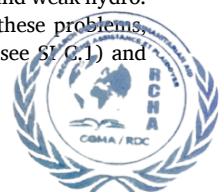
General Referral Hospitals in small, remote, isolated, or “rural” population agglomerations powered themselves through a mix of solar, diesel or hydro generation as available, with the availability of an international support (whether humanitarian or faith-based) that substantially improved power reliability and quality irrespective of power source.

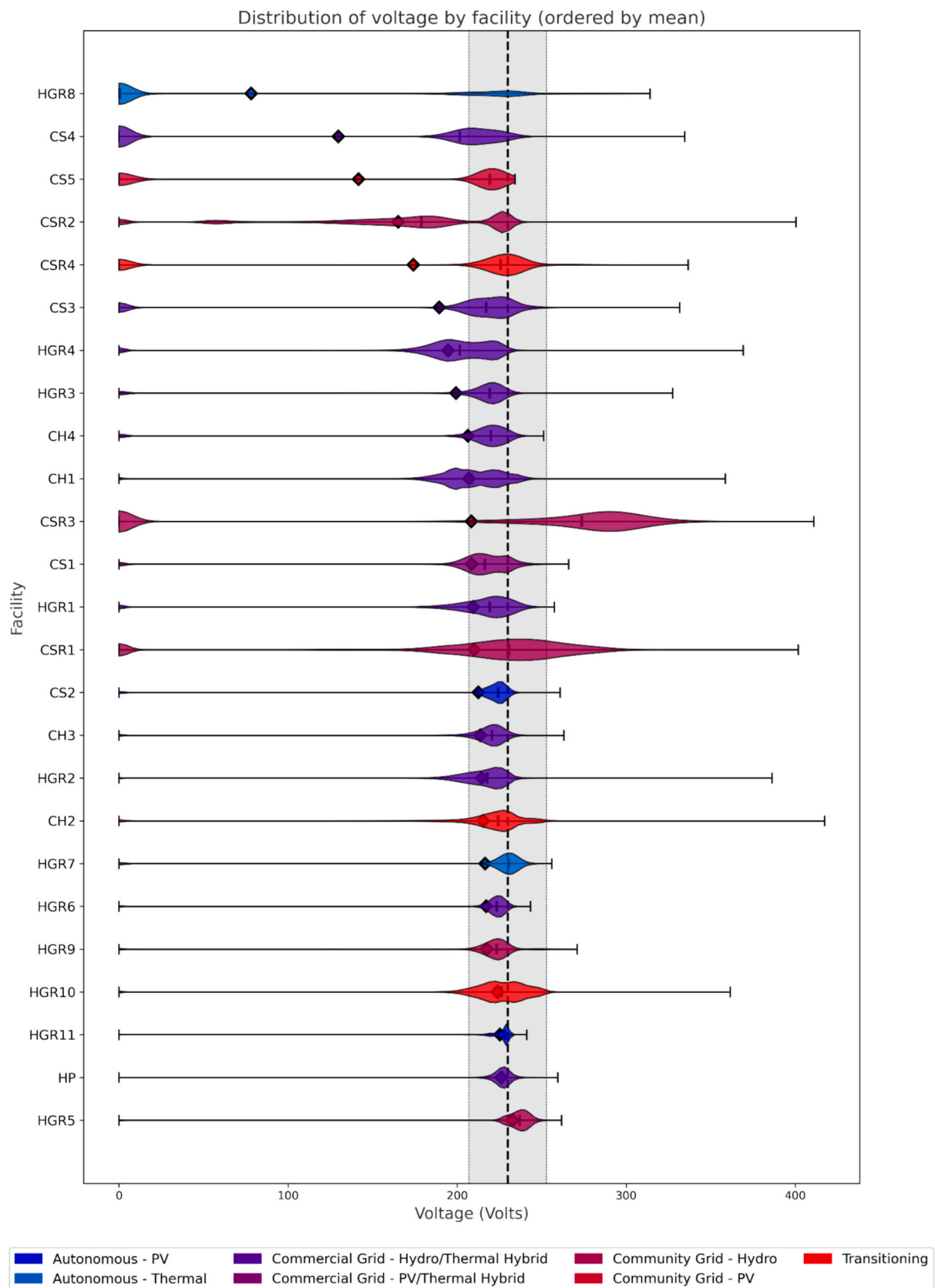
#### 3.3.3. Private hospitals (CH)

CHs typically located in urban centers, tended to exhibit the closest proximity to distribution-level power infrastructure. Private financing (most often faith-based associations, including Catholic and Protestant denominations) enabled them to invest in grid access, backup generators and fuel, solar systems and batteries, resulting in uptime comparable to HGRs. One CH in Goma was connected to two licensed grid providers simultaneously, and switched the entire 400-bed facility three-phase circuitry between the “high-quality but prepaid” commercial electricity grid and the “free but unreliable” government grid based on power interruptions and intuition.

#### 3.3.4. Referral health centers and health centers (CSR and CS)

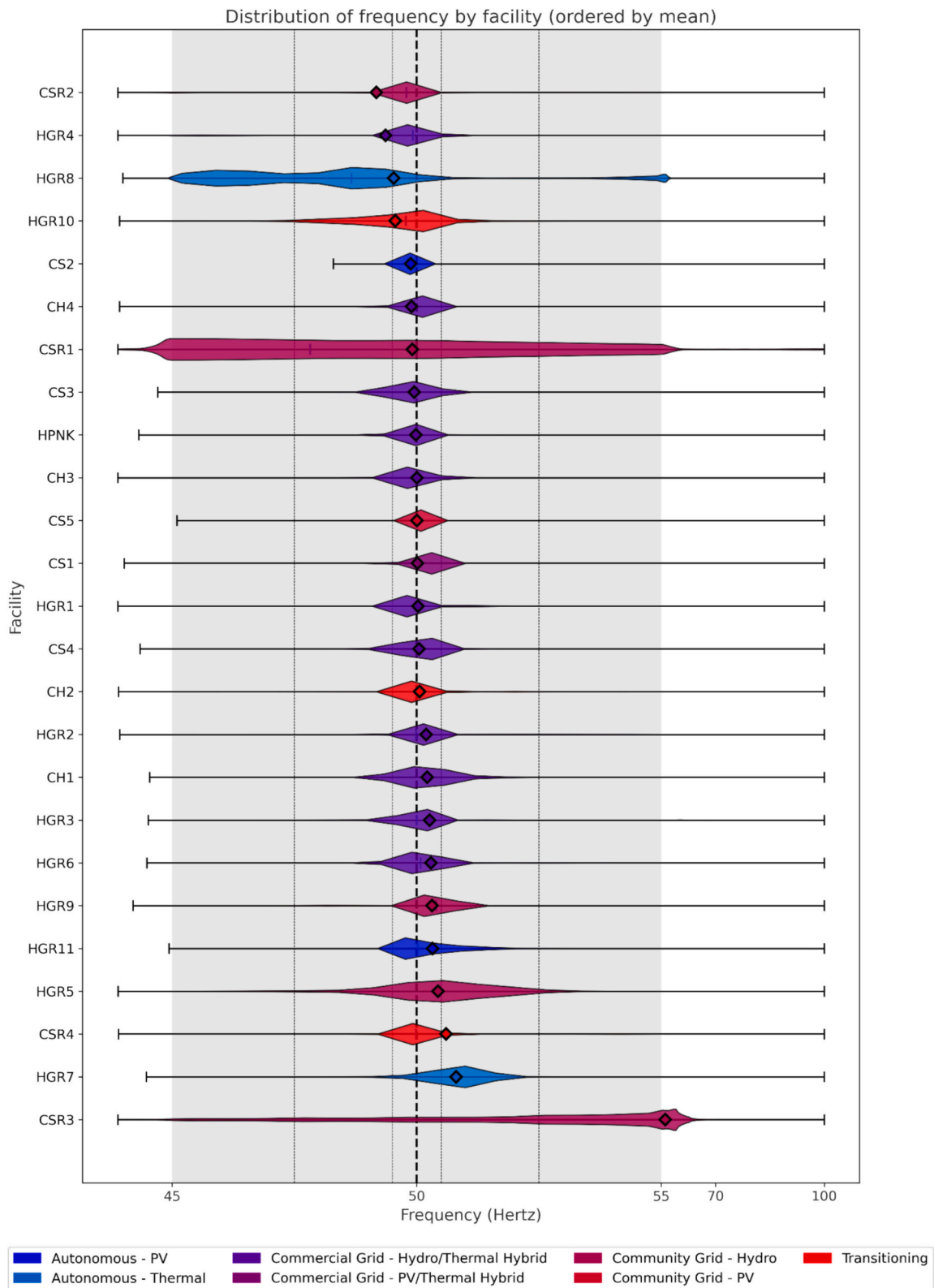
Lower down the referral pyramid are Referral Health Centers and Health Centers. Referral Health Centers faced major energy challenges due to remoteness, low-quality solar, aging generators, and weak hydro. Conflict dynamics and extreme weather compounded these problems, leading to unsafe practices like charcoal sterilization (see SI C.1) and





**Fig. 5.** Voltage from 25 health facilities in North Kivu, DRC. Facilities, anonymized along their facility type designation (HP = Provincial Hospital, HGR = General Referral Hospital, CH = Private Hospital, CSR = Referral Health Center, CS = Health Center), are ordered by mean (indicated by the diamond) and are color-coded by their primary power source, though they may have multiple power sources. The share of each facility’s violin plot that is within the shaded region represents the amount of total time at each facility that was monitored within nominal voltage range (dashed vertical line = nominal 230 V; shaded area =  $\pm 10\%$  of 230 V; diamond = mean voltage).





**Fig. 6.** AC frequency from 25 health facilities in North Kivu, DRC. Facilities, anonymized along their facility type designation (HP = Provincial Hospital, HGR = General Referral Hospital, CH = Private Hospital, CSR = Referral Health Center, CS = Health Center), are ordered by mean (indicated by the diamond) and are color-coded by their primary power source, though they may have multiple power sources. The share of each facility’s violin plot that is within the shaded regions represents the amount of total time at each facility that was monitored within nominal frequency range (dashed vertical line = nominal 50 Hz; shaded areas =  $\pm 10\%$ ,  $\pm 5\%$ , and  $\pm 1\%$  of nominal). Scale on X-axis uses a piecewise linear transformation to highlight the percentage of values within an order of magnitude of nominal ( $\pm 1\%$  and  $\pm 10\%$ ).



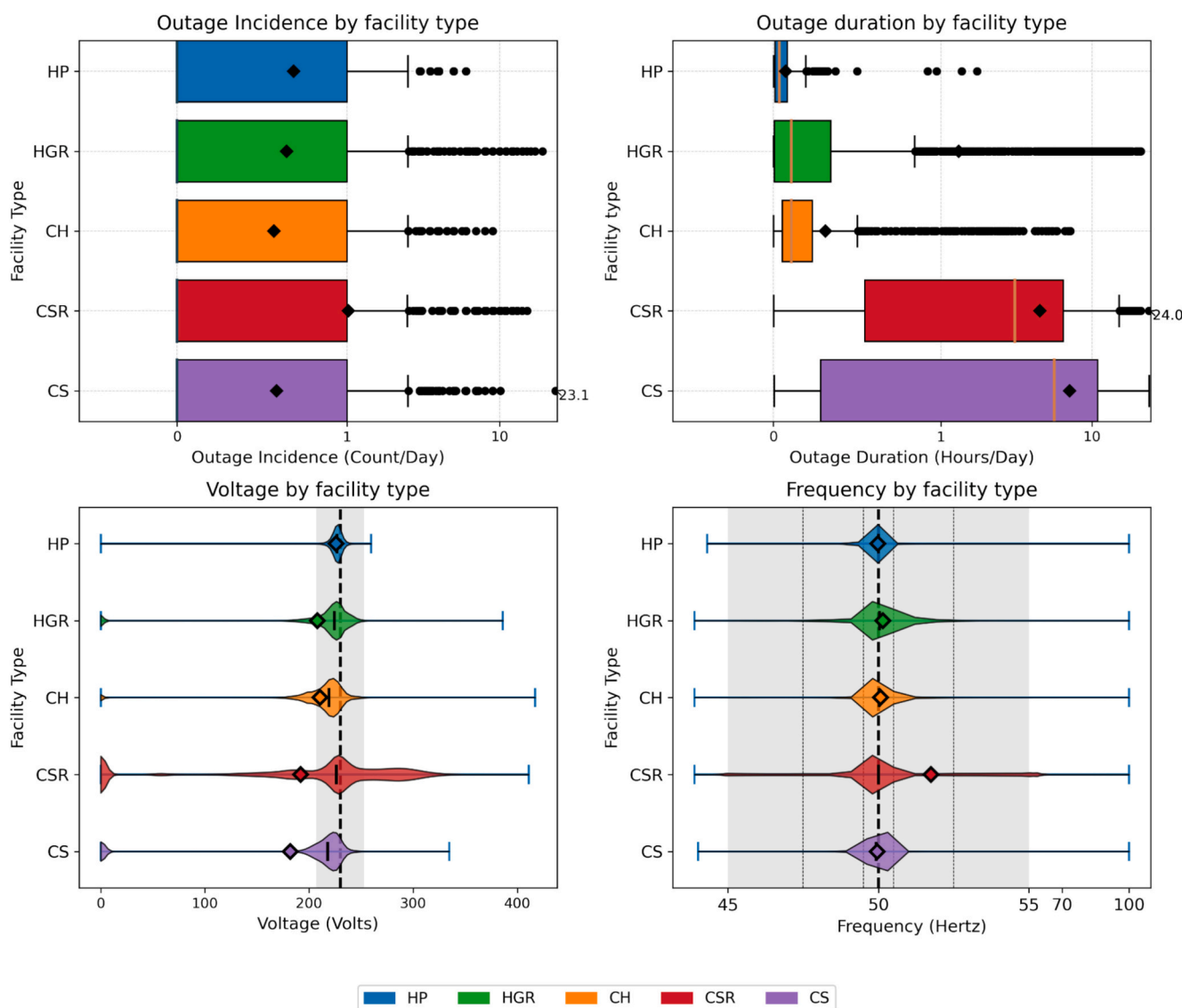


Fig. 7. Power quality and reliability metrics aggregated and colored by facility type, ordered by position in referral pyramid (i.e. HP, HGR, CH, CSR, CS). Clockwise from top-left: outage incidence, outage duration, voltage and frequency.

morgues without any or reliable power to stay cold. Some urban and peri-urban Health Centers were notably “under the grid:” had no grid access despite being in a grid-covered zone, relying instead on clusters of panels and batteries of variable quality (e.g. very good to very poor) across wards.

### 3.4. Power quality and reliability by primary power source

Power quality and reliability metrics across medical facilities in North Kivu revealed significant variation across and within primary power source types (Fig. 8).

#### 3.4.1. Autonomously-powered facilities

Solar power was the most common primary electricity source at study facilities. Across the entire sample of facilities, we observed the highest power quality and reliability in health facilities where high quality solar components were installed and well-maintained. High reliability and staff-reported satisfaction suggest that appropriately-sized, high-quality solar systems can support whole-of-facility essential services when well-maintained. Most facilities relied on local products and installers for meeting basic energy needs through solar assemblages

<5 kW pieced together from locally available components (charge controller, inverter/electric change machine, batteries). Lightning strikes, common in North Kivu, were also noted as particularly dangerous to solar installations in North Kivu by health facility staff.

Three facilities relied on diesel generators as their primary source of electricity. In the one partnered with an international humanitarian organization (MSF), the costs and maintenance of the facility’s diesel generator was managed by and paid for by the humanitarian organization. This facility did not face gaps in power caused by unaffordability and had well-maintained systems, resulting in uptime ranging from 99.9 to 99.99 %, and power quality strictly within nominal thresholds. The other two facilities relying on diesel generation without humanitarian partners reported inconsistent fuel supply and routine maintenance issues, resulting in fuel rationing for emergency or “spot” uses like night lighting or oxygen-supplementation for life support. The spectrum of uptime for facilities powered primarily by diesel generators thus spans the entire range from zero to five nines (0 % to 99.999 %).

#### 3.4.2. Grid-connected facilities

Facilities that were connected to licensed grid operators were primarily located in urban and peri-urban areas. Reliability and quality was



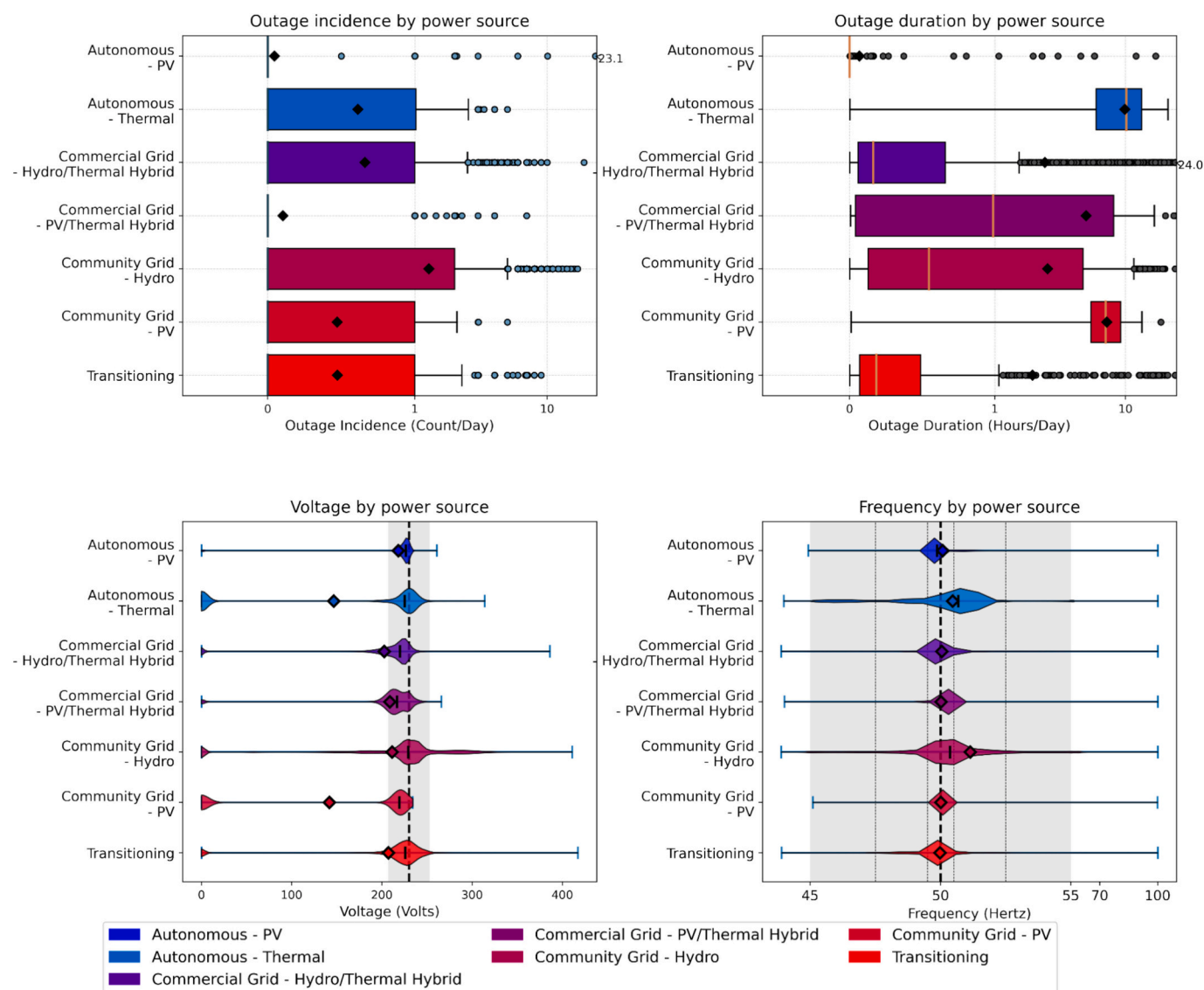


Fig. 8. Power quality and reliability metrics, aggregated and colored by power source type. Clockwise from top-left: outage incidence, outage duration, voltage and frequency.

generally better from private commercial providers than the state-owned utility, but proximity to low-voltage distribution infrastructure (substation/step-down transformers) and the extent of informal connections also had a great impact on power quality (see SI C.2 for photograph of urban informal connection). Commercial grids generally experienced less frequency drift, owing to the mechanical inertia generated by their larger (>1 MW) systems.

Community-managed micro-hydro systems supplied approximately a quarter of North Kivu’s health facility grid connections, principally in tertiary cities and remote agglomerations. While critical to filling health-energy gaps in remote communities, these relatively small systems (<100 kW) exhibited the most serious quality and reliability issues of any power sources in our study, including chronic voltage and frequency well beyond conventional thresholds considered “safe” for typical (unprotected) biomedical equipment. Voltage/frequency deviations and interruptions were qualitatively linked in surveys with older grids, seasonal rainfall and heat, unmet needs for local distribution upgrades (e.g. town-level step-down transformer or substation upgrades), and growth in electrical demand from both community and facility (See SI B.5 for power traces and SI C.3–6 for photographs).

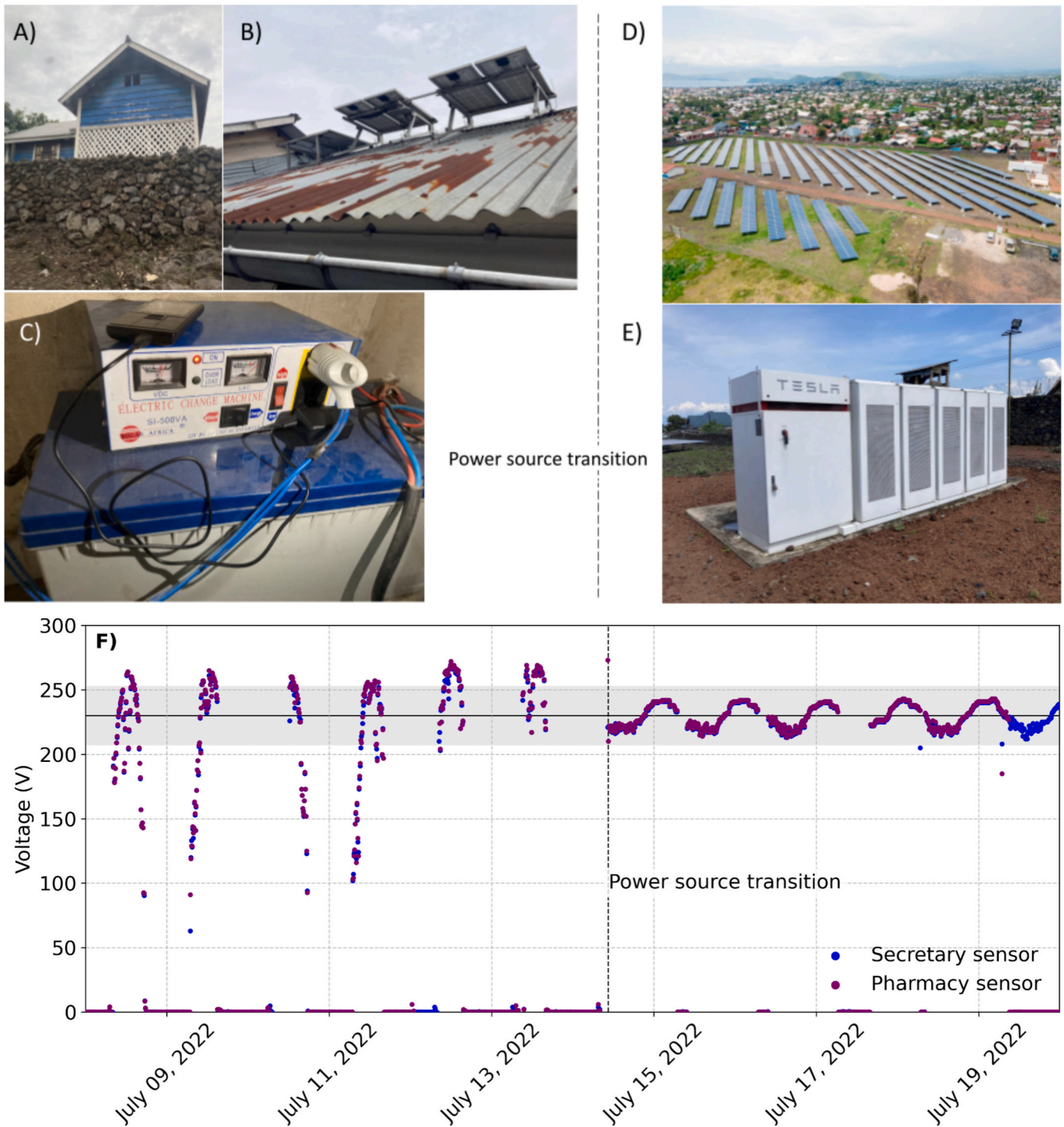
### 3.4.3. Transition facilities

Three facilities’ primary power source changed during the course of the monitoring period. Power quality and reliability improved in all three transition cases. HGR10 transitioned from generator power to commercial hydro and CH4 transitioned from a community hydro to commercial hydro. CSR4, a peri-urban facility at the edge between the Goma urban core and the forested Nyiragongo territory, initially relied on a fragile 3–5 kW solar assemblage with voltage fluctuating by sun angle (Fig. 9). It relied on an “electric-change machine,” local-market inverters that convert solar-DC power to outlet-AC electricity, ubiquitous across health facilities in the province. After connecting to a large PV metro-grid, its power stabilized with far fewer outages and consistent voltage and frequency.

## 4. Discussion

### 4.1. Comparison with health facilities in other LMIC geographies

The use of objective PQR metrics enables a robust comparative analysis of electricity across LMIC health settings. Health facilities in North Kivu had fewer outages but longer outage durations compared to



**Fig. 9.** Transition case: micro-solar to metro-grid upgrade at peri-ruban Referral Health Center A) CSR4 at beginning of study B) solar assemblage C) battery and “electric change machine”; D) aerial view of the peri-urban PV metro-grid CSR4 was connected to in July 2022; E) Commercial PV-grid battery storage; F) Voltage during the transition week at CSR4. (Photos: S Miles and Global Energy Alliance for People and Planet).

facilities in Nigeria and Kenya; among facilities in North Kivu, the average daily outage incidence was 0.67 outages per day (~5 outages per week), compared to 2.05 outages/day (~14 outages/week) in Nigeria ( $n = 93$  facilities monitored for 18 months) and 1.33 outages/day (~9 outages/week) in Kenya ( $n = 210$  facilities monitored for 18 months) [35]. However, the median outage duration recorded in North Kivu was 2.01 h, significantly longer than the average in Nigeria (6.0 min) and Kenya (1.2 min).

The North Kivu facilities experienced better voltage than Nigerian

facilities, but worse frequency than either Nigerian or Kenyan ones. Voltage in the North Kivu sample was within  $\pm 10\%$  of nominal range 73.9% of the time, significantly better than 27% in the Nigerian sample but lower than the 87% in Kenya. The AC frequency in North Kivu facilities was within  $\pm 10\%$  of the nominal range 84.9% of the time, lower than both Nigeria at 97.8% and Kenya at 99.9% [35].

Differences in PQR and their association with different power sources suggest how different solutions might be prioritized in a given context. For example, to increase uptime and improve quality, North



Kivu should prioritize energy production and storage capacity, as well as frequency stabilization at micro-hydro-powered facilities. In Nigeria, on the other hand, frequent but short outages, along with systematic undervoltage, might be best addressed in the short term with uninterruptible power supplies (UPS) and voltage stabilizers.

The study’s findings underscore the value of considering the type of power source and facility type when assessing power quality and reliability. Facilities powered by community-managed micro-hydro systems — particularly older and smaller ones — exhibited many of the challenges facing “pico-hydropower technologies” like the maintenance and repair of turbines, dealing with variation in the water flow between seasons, and the ability to maintain income generating loads [36]. In contrast, facilities with high-quality solar systems and well-maintained backup generators tended to have better power quality and reliability.

4.2. More accurately and precisely capturing power quality and reliability data

The World Bank’s Multi-Tier Framework for Electricity Access [37] has been adapted by the World Health Organization to assess electrification levels in health facilities [13]. However, significant evidence gaps have constrained efforts to characterize appropriate technical thresholds across the five tiers. Updating the definition of reliability from one emphasizing only outage duration (i.e. “Was there an outage of >2 hours in the past week at your facility?”) to one reflecting uptime would serve two important purposes: 1) revealing the variability in interruption incidence and duration that a binary definition fails to capture and 2) leverage a widely adopted and easily understood convention for quantifying the reliability of electricity and telecommunications [38]. Such approaches have already gained practitioner momentum as well as empirical evidence of impact in improved delivery in rural water sectors in LMICs, for example a decrease in pump downtime from an average of 27 days to 2.6 days in Rwanda [39,40].

The study’s findings extend the small but growing body of sensor-based studies on health facility electricity by demonstrating feasibility in a conflict-affected, francophone LMIC setting where both grid and off-grid systems are highly fragmented. The data suggest distinct power protection regimes may be required across countries, and highlight valuable information for infrastructure expansion planning and performance-based financing. In addition to improving global electrification progress monitoring and planning, technical disparity metrics could inform energy justice indicators to more equitably deploy power and health investments.

4.3. Limitations

Facilities selected for monitoring were intentionally selected to reflect the widest possible representativity of the province in terms of patient volumes, and was thus biased towards facilities along the main demographic North-South axis running through Beni, Butembo, Lubero, and Goma. Remote facilities selected to balance representativity necessarily had a power source to monitor, biasing our monitored sample towards facilities with some form of electrification and accessibility. Surveys were deployed only once per respondent, and thus gave limited insight into seasonality. Increased automation in direct-respondent data collection could enable the regularity needed to observe seasonal or exogenous effects. Though surveys were administered through the health administration’s official protocol, response remuneration may have created an incentive bias for facility staff to underreport existing energy assets. Our small sample (n = 25 facilities) limited statistical power, so group comparisons should be interpreted as exploratory. While facility-level metadata are provided to support transparency, we anonymized facility identities to preserve confidentiality in an active conflict setting, which may limit exact replication of the sample. Finally, the deep roots of organized violence and humanitarian presence in North Kivu is likely more representative of conflict-

affected areas than peaceful LMIC geographies.

4.4. Future research: Biomedical equipment failures and indicators to support patient outcomes

The main health impacts of PQR are likely felt via the degradation and premature failure of biomedical equipment [41,42]. Most research on power quality’s impacts on biomedical equipment LMICs focuses on voltage [11,35,43], but AC frequency issues could lead to faster or slower than intended motor operations, potentially interfering with high precision dosage needs like anesthetics or causing irreversible equipment damage through uncontrolled current surges. This highlights the need to test standard, unprotected equipment against power quality exposures such as those measured in this study, to assess whether the existing protection standards align with the operational realities of LMIC power systems.

Future research could strengthen the connection between electricity reliability and health outcomes by incorporating proxy indicators of biomedical equipment failure and service disruptions (see Table 5). Facility technician logs, maintenance schedules, and the existing monthly health reporting variable on “number of days equipment is out of use” could provide valuable intermediate measures, though these data are currently not systematically submitted to the health data reporting system. Additional indicators, such as patient counts, ward-level deaths, or interruptions in critical services (e.g., sterilization, oxygen delivery), may help further establish causal pathways between poor power quality, equipment downtime, and adverse patient outcomes.

We recommend future research expand on sensor deployments to capture seasonal and environmental diversity relevant to the design of biomedical equipment (e.g. lightning density, temperature, humidity, particulate matter). With additional monitored data and information on equipment failure and tolerance ranges, local voltage and frequency conditions could be explored to map electricity-biomedical equipment failure pathways and needs more precisely. This could lead to the development of more appropriate power acceptability curves [44],

Table 5  
Policy recommendations.

Data collection and dissemination custodians	<ul style="list-style-type: none"> <li>● Replace binary reliability definitions with more nuanced PQR or uptime-based metrics. Current WHO and MTF indicators miss frequent short outages, voltage sags, and frequency instability. Continuous sensor-based monitoring with uptime benchmarks provide more actionable benchmarks.</li> </ul>
Researchers and policy-makers	<ul style="list-style-type: none"> <li>● Integrate energy and health data. Linking PQR metrics with biomedical equipment logs, patient counts, and ward-level mortality would enable stronger causal inference to guide donor and government investment and policy.</li> <li>● Use real-time “big data” for health–energy planning. Aggregated sensor data can flag hospitals with the most significant outages or quality challenges, guiding targeted upgrades (e.g., oxygen circuit backup, solar/battery reinforcement, or micro-hydro stabilization) and helping ministries and donors allocate resources where health gains will be greatest.</li> </ul>
Health and energy government agencies	<ul style="list-style-type: none"> <li>● Prioritize vulnerable facilities and critical equipment. Remote referral centers and small solar or aging micro-hydro systems showed the poorest PQR performance in our study. Upgrading such sites and protecting circuits for critical equipment with secure, high-quality power could yield the most cost-effective health gains in the immediate term.</li> </ul>
Health system funders and investors	<ul style="list-style-type: none"> <li>● Invest in scaling sustainable financing pilot models. Real-time reliability data can underpin performance-based contracts, energy-as-a-service models, and donor accountability mechanisms.</li> </ul>



which define the likely impact of power on electronic devices based on the magnitude and length of exposure to deviations from manufacturer ratings, specifically for donation-based and/or designed-for-LMIC biomedical equipment.

These data might help health systems with more precise guidance on which outlets, equipment, and wards should only be used on facility circuits that are “secured” (highly protected from interruptions and quality issues), “non-secured” (susceptible to outages and non-conditioned voltage and frequency) and “non-critical” circuits (power sources without any backup, voltage or frequency control) [45]. Statistical analysis of power and seasonal environmental indicators (temperature, precipitation) could enable more geographically and environmentally-sensitive energy planning decision-making tools.

## 5. Conclusion

This study of 25 health facilities in North Kivu, DRC demonstrates that real time power sensors have the ability to capture the incidence and duration of outages, voltage and frequency for facilities using a range of power sources. By demonstrating the feasibility of continuous, auditable monitoring in a conflict-affected LMIC, we suggest that sensor-based metrics may provide more sensitive and clinically relevant indicators of electricity performance than existing WHO and MTF survey frameworks alone.

PQR indicators can be used to calculate facility- or ward-level electricity uptime, which provides far greater insight into a facility’s access to electricity than the existing binary based on recall of an outage >2 h in the past week currently employed by official survey tools. Health facility survey tools should be calibrated to sensor-reported benchmark indicators for reliability. This could enable replicable segmentation of facilities in other geographies into easily tiered categories, for example, based on outage profiles reflecting a two-hour outage once a week (~99 % uptime) or once a day (~92 %).

Electricity data associated with different types of facilities and power sources can help prioritize interventions to address poor power quality and reliability. The integration of high quality, low-latency operational metrics opens new possibilities for testing sustainable delivery models, whether along the “uptime” ladder of power system reliability for potential energy-as-a-service operators, or more patient/health facility-centered metrics linked to health outcomes like mortality reduction.

The findings support updating global electrification metrics to incorporate real-time uptime, voltage, and frequency indicators that better capture risks to biomedical equipment and patient outcomes. Further cross-country research would deepen our understanding of the impacts of power quality and reliability on healthcare outcomes, particularly at the “last millimeter” level of individual wards, patients, and biomedical devices.

## Declaration of generative AI and AI-assisted technologies

During the preparation of this work the authors used ChatGPT in order to iterate on code for data visualization in Python. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## CRedit authorship contribution statement

**Samuel B. Miles:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jackson M. Mughuma:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Magda Moner-Girona:** Writing – review & editing, Visualization, Conceptualization. **Daniel M. Kammen:** Writing – review & editing, Writing – original draft,

Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Laura H. Kwong:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

The authors acknowledge reviewers’ thoughtful comments. SM gratefully acknowledges Dr. Alexandra (Sascha) von Meier, Noah Klugman (nLine.io), Rod Hinman (Global Health Labs, Inc), Dr. Rebecca Hernandez and Sienna Levine (UC Davis), Kyle Hamilton (Nuru SASU), the Renewable and Appropriate Energy Lab and African Great Lakes Lab Group (UC Berkeley), Lukas Müeller & Bastian Herzog (A2EI), CITRIS and the Banatao Institute, the Link Foundation. DK gratefully acknowledges support from the Lau Foundation and the Karsten Family Fund. This material is based upon work supported by the National Science Foundation under Grant No. DGE- 2125913. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2025.126830>.

## Data availability

Data will be made available on request.



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