Power Quality Challenges in Low-Resource Settings

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1 Executive Summary

Unevenness in the availability and quality of mains electricity can pose considerable challenges to low- and middle-income countries (LMICs), both in terms of economic development and implementation of essential public sector services such as health care delivery. This is particularly true in health care settings where alternating-current (AC) electrical power is required to support priority medical equipment such as vaccine refrigerators and freezers, diagnostic equipment, and oxygen concentrators. We analyzed voltage and other power measurements collected by mains-powered vaccine refrigerators operating in health facilities in Kenya and Nigeria to illuminate power availability and quality in these settings. These analyses should prove valuable for specifications- and standards-setting bodies, equipment designers, and equipment purchasers.

Our team collaborated on the design of the Aucma CFD-50 vaccine refrigerators (hereafter referred to as *devices*) used in the study. In Kenya, 210 devices were installed in individual health facilities in 36 counties in collaboration with the National Vaccines and Immunization Program (NVIP), with 176 devices purchased by the Government of Kenya and the remainder purchased by The Global Good Fund I, LLC (GGF). In Nigeria, 93 devices were installed in 8 states and the Federal Capital Territory in collaboration with the National Primary Health Care Development Agency (NPHCDA), with all devices purchased by GGF. Data collection began as devices were installed beginning March 9, 2018 and continuing until August 31, 2019. All devices reported power data for at least 1.5 continuous months, with an average of 10 months of data reported per device. We found the following:

Reported voltages deviated significantly from nominal, so voltage stabilization can improve equipment availability.

Electrical equipment is generally designed to operate over a relatively small range of voltages, often ±10% from an ideal or nominal value. Voltage fluctuations beyond that amount can reduce performance or damage the equipment. Voltage stabilizers can be used to extend the usable range. Figure 1 shows an overview of all voltage samples gathered over all devices during the study, splitting them into three groups: usable without a stabilizer, usable if stabilized, and unusable.

In Kenya, power was usable 87% of the time, and usable if stabilized an additional 3% of the time. The remaining 10% unusable represents over 2 hours per day for each device on average. Because voltage stabilizers add about 3% of additional time of usable power, they may not be warranted for every location, but certain locations disproportionately experience voltage deviations and would benefit from stabilization. In Nigeria, devices reported usable voltage 27% of the time, and usable if stabilized an additional 15% of the time, suggesting that voltage stabilizers could be broadly useful.

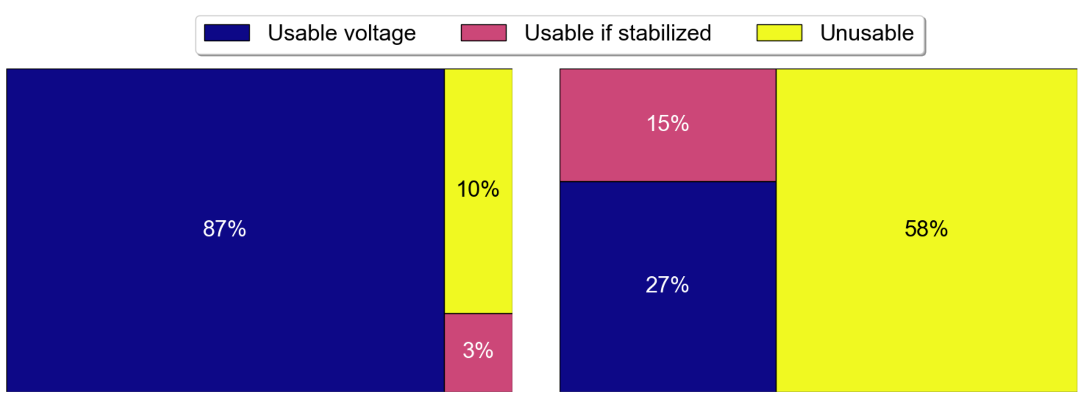

Figure 1: Percentage of time that mains voltage was usable without a stabilizer, usable if stabilized, and unusable. (Kenya on left, Nigeria on right)

Voltage stabilization, however, cannot fix every situation because it cannot provide adequate voltage when there is a complete interruption in service.

Interruptions were common, and many health facilities experienced them.

Interruptions in electrical service were commonly reported throughout the study period and in both countries, many long enough to disrupt operation of equipment at health facilities. For example, interruptions greater than 48 hours can compromise the ability of common ice-lined vaccine refrigerators to maintain safe vaccine storage temperatures.

In Kenya, during the study period across all devices there were 465 reported interruptions longer than 48 hours, which averages to 2.5 interruptions for each device per year. The left side of Figure 2 shows how these interruptions were distributed among devices by categorizing each by the average number of these longer interruptions per year. Thirty-two percent (32%) of devices reported no interruptions longer than 48 hours, and 60% reported between 0 and 6.0 interruptions longer than 48 hours per year, on average. The remaining 8% of devices reported between 6.0 and 42.6 interruptions longer than 48 hours per year, on average.

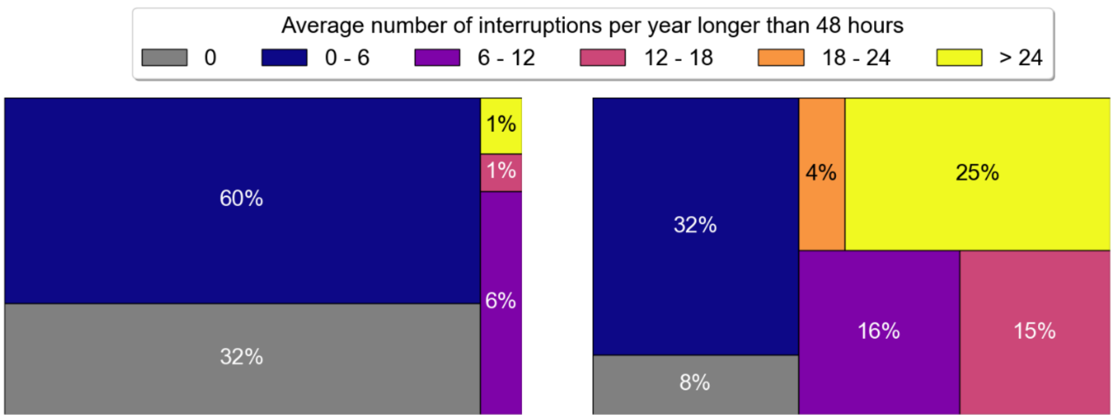

Figure 2: Percentage of devices reporting interruptions longer than 48 hours per year, on average (Kenya on left, Nigeria on right) Due to rounding, percentages may not sum to 100%.

In Nigeria, there were 1,145 reported interruptions longer than 48 hours, which averages to 15.1 interruptions for each device per year. Eight percent (8%) of devices reported no interruptions longer than 48 hours, and 32% of devices reported between 0 and 6.0 interruptions longer than 48 hours per year, on average. The remaining 60% of devices reported between 6.0 and 73.8 interruptions longer than 48 hours per year, on average.

Extreme voltage conditions can pose a risk of permanently damaging medical equipment.

In both countries devices reported voltage conditions that can potentially permanently damage improperly protected equipment. Devices reported hours- or days-long periods where the voltage changed by as much as 60 V within 10 seconds. Rapid voltage changes such as these can be challenging to stabilize and pose risks both to stabilizers and to the equipment they protect. Devices reported sustained (longer than 1 minute), severe high voltages in both countries in excess of 350 V and even 450 V, which can damage equipment by breaking down insulating layers and causing high currents. While these conditions occurred far less frequently than interruptions, they are critical to consider in medical device design because even a single event can negatively impact health facility operations.

2 Introduction

Approximately 1.1 billion people worldwide do not have access to electricity. Another billion have access, but the availability and quality of electrical service is compromised [WBGEval2014]. The World Bank Group's (WBG) energy sector development programs seek to improve power quality and increase access to electricity[1,2]. Projects funded by the WBG's International Development Association in Kenya led to a 38% reduction in distribution line interruptions between December 2004 and September 2013[3] [P083131] and in Nigeria led to improved end-user voltage[4] [P090104].

Sustainable delivery of primary health care interventions, such as immunizations, in LMICs' public sector health facilities relies upon many factors including reliability of medical equipment. Such equipment may be rendered inoperable amidst conditions facing many health facilities in LMICs. Examples of such conditions include intermittent power availability coupled with a lack of alternative power sources such as solar inverters or diesel generators, as well as highly variable power quality leading to stressing or failure of components [Bonnett1999, Frost2013]. This equipment is often expensive to acquire and typically relies on routine maintenance to optimize performance. In public sector health facilities, these issues may be further compounded by financial and/or human resources hurdles constraining routine preventive maintenance and non-routine servicing of medical equipment.

The current dearth of data on power conditions facing public sector health facilities in LMICs poses challenges to evidence-based policymaking. Profiling the electrical power available to primary health care facilities in low-resource settings can inform product specifications and standards; product design; selection among products; procurement and maintenance; and planning for the performance, reliability, and lifespan of medical devices and equipment in LMICs. To help mitigate significant mains power quality and availability gaps in the near term, some LMICs opt to prioritize procurement of far higher cost solar-powered vaccine cold chain equipment for use in certain health facilities. See sidebars, *Evidence-Based Decision Making in Kenya* and *Evidence-Based Decision Making in Nigeria* on the next page.

To illuminate power availability and quality challenges facing health facilities in low-resource settings, we analyzed data on voltage and frequency collected by World Health Organization (WHO)–prequalified mains-powered vaccine refrigerators (Aucma CFD-50[5]) in 303 health facilities across Kenya and Nigeria over a nearly 18-month period, from March 2018 through August 2019, in collaboration with Kenya's National Vaccines and Immunization Program (NVIP) and Nigeria's National Primary Health Care Development Agency (NPHCDA).

These longitudinal data and our findings may prove valuable for the following user groups and purposes:

- **Financers and purchasers of medical devices and equipment such as Ministries of Health and Finance in LMICs, UNICEF, bilateral and multilateral development organizations, and philanthropic foundations:** To

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[1] https://www.worldbank.org/en/topic/energy.

[2] https://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/infrastructure/priorities/power.

[3] Number of "combined monthly distribution line interruptions per 100km, for 66 kV and 33 kV lines" dropped from 4.7 in December 2004 to 2.92 in September 2013. [IDA2013]

[4] Baseline metrics of voltage improvement and the dates thereof differ between the project website (http://projects.worldbank.org/P090104/nigeria-national-energy-development-project?lang=en&tab=results) and the ICR Report [P090104]

[5] http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/LinkPDF.aspx?UniqueID=16d75030-c499-4746-89c9-f96d0d327109&TipoDoc=DataSheet&ID=0.

improve the quality of health care in low-resource settings by improving the performance, reliability, and lifespan of medical devices and equipment deployed in LMICs.

- **Specification developers and standards-setting bodies such as Ministries of Health and National Regulatory Authorities in LMICs, WHO, and UNICEF:** To inform the generation of relevant and adequately stringent specifications for priority medical devices and equipment intended for use in LMICs.
- **Device and equipment designers**: To inform product development and anticipate resource needs associated with product warranties.

Evidence-Based Decision Making in Kenya

In Kenya, this power data analysis is already helping us make decisions on what types of vaccine refrigerators and voltage stabilizers are needed for some health facilities based on their specific power profiles over time, including voltage, frequency and interruption data. For example, we learned some health facilities with mains power have extended blackouts for 3 to 4 days per week, but we know most WHO-prequalified mains vaccine refrigerators cannot keep vaccines at safe temperatures in such situations. If we collect enough power quality data from all over the country, we can better understand power profiles nationwide and make informed decisions on what types of vaccine refrigerators and other medical devices, equipment and systems are needed to address our needs.

- Ernest Some, Head/CTO, Cold Chain, National Vaccines and Immunization Program (NVIP)

Evidence-Based Decision Making in Nigeria

As evidenced in the study, access to reliable electricity in health facilities across Nigeria remains constrained and limited, the situation is further exacerbated by a high number of interruptions and a very high percentage of unusable voltage. It is this kind of information and data that has informed the policy of the country: to have one functional Cold Chain Equipment in each of the over 9656 political wards in the country, thereby massively expanding cold chain storage capacity and addressing supply-side barriers to immunization service delivery. The National Primary Healthcare Development Agency in implementing this policy is prioritizing solar direct drive (SDD) cold chain equipment installation at facilities with significant power quality challenges. Gavi support for the expansion is being leveraged through the Cold Chain Equipment Optimization Platform (CCEOP) to procure over 12,700 CCE, of which most are SDDs.

- Hajia Kubura Daradara, Director Logistics and Health Commodities, National Primary Health Care Development Agency (NPHCDA)

2.1 Power Profile Data Collection

Power availability and quality are monitored worldwide, primarily for use by electric utilities or specialized consumers like factories with industrial processes that cannot tolerate disruption. Some data collection efforts in LMICs are:

The Electricity Supply Monitoring Initiative (EMSI), developed and led by Prayas (Energy Group), an Indian non-governmental organization, monitors electricity supply at 434 locations across 23 states of India [EMSI]. It is the most substantive data set we know of, containing six years' data in some locations. EMSI also has monitors in the Nairobi, Kenya, area [EMSI_KE], Tanzania [EMSI_TZ], Tajikistan [EMSI_TJ], and Indonesia [EMSI_ID][6]. The monitors

[6] https://watchyourpower.org/esmi_beyond_india.php.

capture interruptions and voltage levels and transmit them to a central server. Monthly reports are generated summarizing power quality across India, detailing the number of interruptions of different lengths experienced and how many interruptions occur in the evening hours[7]. EED Advisory Limited reported on Kenya power using EMSI data from November, 2017. During that month, 62% of the 39 EMSI locations in Nairobi experienced outages for more than 15 hours [EED2017].

As part of a study on powering broadband communications networks in low-resource settings in the rural Mara region of northern Tanzania, Nungu et al. analyzed two months of data [Nungu2011]. They observed an average of two power interruptions per day, with a maximum of 21 interruptions on a single day. They attributed some interruptions to poor wiring or other infrastructure problems; other interruptions were planned rationing of scarce generator power.

FNET/GridEye, a project run by the University of Tennessee, Knoxville (USA), uses frequency disturbance recorders (FDRs) to monitor system frequency in many places around the world [FNET]. Although FNET/GridEye, through its industry consortium, has stations spanning North America, Europe, and parts of Asia, currently it has limited presence in LMICs and none in sub-Saharan Africa[8]

The system frequency of the Nigerian electrical grid has been monitored at locations in Bauchi State [Vanfretti2009] and Kaduna State [Mohammed2017]. Frequency disturbance recorders measured voltage and frequency at single points in the electrical grid. Both researchers found the Nigerian electrical grid to have loose frequency regulation, and Mohammed noted that frequency variation in 2017 (range of 48.99 Hz to 51.65 Hz, standard deviation 0.54 Hz) was greater than the variation in previous years.

The Systems Toward Infrastructure Measurement and Analytics (STIMA) Laboratory at the University of Massachusetts, Amherst (USA), has conducted an analysis of interruption patterns in Nairobi, Kenya, using Kenya Power and Light Company's (KPLC) customer complaint and system mapping data over the course of a year, in 2014 and 2015 [Taneja2017]. They found interruptions mostly occurred in the mornings and evenings and that roughly half were from the failure of a single phase at the block or neighborhood level. The same group at STIMA has also demonstrated that software for a smartphone can be used in conjunction with a tabletop fan to estimate the voltage at the outlet where the fan is powered [Breda2018]. A low-cost solution such as this could help monitor power quality over a wide area, if individuals are properly incentivized to participate.

A research group at the University of California, Berkeley (USA) studied household power quality in Unguja, Tanzania [Jacome2019]. They monitored voltage at a total of 14 locations along two utility feeders from December 2016 to June 2017, as well as conducted interviews about customer experiences with power quality. They found that in general houses toward the far end of feeders experienced greater variation and lower average voltages than those near the transformer. Voltage data were correlated to customer experiences with flickering lights and damaged equipment. They conclude that, "On the Unguja grid, the ability to benefit from the basic accoutrements of modern life … is not guaranteed."

Despite the valuable information generated by these institutions and organizations, none of the aforementioned efforts measured power profiles within health facilities in LMICs.

eHealth Africa studied power conditions in 22 health facilities in 3 states in northern Nigeria over a 6-month period in 2014 [Patil2015]. These facilities had access to both the national electrical grid and to generators. Voltage data loggers were used to measure voltage at the outlet at 5-minute intervals. The authors found 10,298 complete interruptions during the study period. The median duration for these interruptions was 30 minutes, and 11.6% of

[7] http://watchyourpower.org/uploaded_reports.php
[8] http://powerit.utk.edu/worldmap/.

them (1,196) lasted longer than 8 hours. Voltage was low (10 V to 220 V) 26.7% of the time, and 3% of the time it rose above 240 V.

Our study follows a similar approach to that taken by eHealth Africa, except that measurements were made using vaccine cold chain equipment (CCE) rather than dedicated data logging devices. Our study also included data reported by devices operating in a larger number of health facilities (303) for a longer period of time (nearly 18 months).

2.2 Relevant Standards

The Institute of Electrical and Electronics Engineers (IEEE) has developed several standards and recommended practices related to power quality [IEEE1366] and power quality monitoring [IEEE1159].

The International Electrotechnical Commission (IEC) also has created standards for power quality on the supply and equipment sides of the point where the electricity customer connects to the utility's system. Many of IEC's standards have been adopted as European Standards (ENs). IEC/EN 50160 [IEC50160] sets out recommended power quality conditions for a power distribution system that many countries have used as a basis for national power quality regulations. The IEC 61000 series of standards covers characteristics of the electricity supply system and customer equipment. Part 2 of IEC 61000 comprises standards describe the "environment," or the limits on power quality disturbances created by the electricity supply system. Other parts of IEC 61000 define how much end equipment can degrade power quality through its interaction with the electricity supply system and describe the non-ideal conditions that equipment must be able to withstand.

Of particular interest to equipment manufacturers are IEC 61000-4-11 [IEC61000-4-11], which describes tests for immunity to short voltage dips and interruptions, and IEC 61000-6-1 [IEC61000-6-1], which sets the limits to be used in those tests.

Given the extent of voltage variation experienced in many LMICs, health facilities in these countries commonly use voltage stabilizers to mitigate damage to medical devices and equipment resulting from overvoltage and undervoltage conditions. WHO's Performance, Quality, and Safety (PQS) Secretariat establishes performance specifications and standards for immunization-related devices and equipment and prequalifies such products for procurement by United Nations agencies [PQSCat]. The PQS Secretariat has published a standard for voltage stabilizers for use with immunization-related cold chain equipment, such as vaccine refrigerators and vaccine freezers: WHO/PQS/E007/VS01.5 [PQSVS01]. This standard defines stabilizers as 230 V/50-60 Hz "extended" if they can convert the input range 110 V to 278 V into an output range that is suitable for 230 V to 240 V equipment[9]. Mains voltage within this 110 V to 278 V range is thus dubbed "*usable with stabilization*."

[9] The output must be in the range 230 V +10% and -15%, or 195.5 V to 253 V, over the range from zero load to its rated load. From [PQSVS01], clause 4.2.7.

3 Definition of Terms

3.1 Acronyms

AC – Alternating Current. Refers to power systems characterized by voltage and current that alternate in polarity, typically cycling 50 or 60 times per second (50 Hz or 60 Hz).
ADC – Analog-to-Digital Converter. An electronic circuit that produces a digital representation of a measured signal.
CCE – Cold Chain Equipment. Equipment meant to keep medical supplies, often vaccines, at a controlled temperature.
FCT – Federal Capital Territory of Abuja, Nigeria.
FDR – Frequency Disturbance Recorder.
GGF – The Global Good Fund I, LLC.
IEC – International Electrotechnical Commission.
IEEE – Institute of Electrical and Electronics Engineers.
KPLC – Kenya Power and Light Company.
LGA – Local Government Area. A local government division in Nigeria that subdivides states.
LMIC(s) – Low- and middle-income country/countries.
NPHCDA – National Primary Health Care Development Agency (Nigeria).
NVIP – National Vaccines and Immunization Program (Kenya).
PHC – Primary Health Care.
PQS – Performance, Quality, and Safety Secretariat. A WHO team that establishes performance specifications and standards for immunization-related devices and equipment.
RMS – Root mean square. A common method of calculating voltages and currents in AC power systems.
UNICEF – United Nations Children's Fund.
UPS – Uninterruptable power supply.
WBG – World Bank Group.
WHO – World Health Organization.

3.2 Other Terms

The definitions of terms can vary across the electrical power industry, so we define how terms are used for the purposes of this report. Some of these terms can be visualized in Figure 3, which shows voltage ranges and an example graph of voltage over time. The example traverses all the voltage ranges.

Nominal voltage and frequency: The expected values of voltage and frequency at the electrical outlet. The nominal grid voltage in Nigeria is 230 V[10], while in Kenya it is 240 V[11]. In both countries, power system frequency is 50 Hz, with a desired range between 48.75 and 51.25 Hz[12, 13].

Usable Voltage or Normal Voltage: When the voltage at the outlet is within ±10% of the nominal voltage, 216 V to 264 V for Kenya and 207 V to 253 V for Nigeria. Equipment is often designed to operate over a similar range. We also say that *power* is usable when the voltage is in this range, meaning that equipment can draw power from the mains.

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[10] [GRID_N1] Section 4.3, p. 34: 230 V ±6%, or 216.2 V to 243.8 V.
[11] The National Distribution Code [GRID_K1] does not specify nominal voltage for customers, only tolerances about the nominal (±6% for urban and ±10% for rural). [GRID_K2] Describes tariffs for supply to customers at 240 V and 415 V.
[12] [GRID_N2] Section 10.1, p. 47, "The National Control Centre will endeavour to control the System Frequency within a narrow operating band of +/- 0.5% from 50Hz (49.75 – 50.25 Hz), but under System Stress the Frequency on the Power System could experience variations within the limits of 50 Hz +/- 2.5% (48.75 – 51.25 Hz)."
[13] [GRID_K1] Chapter 5.5.2, p. 80.

Usable with Stabilization: When the voltage is between 110 V and 278 V, the range defined by the WHO PQS voltage stabilizer specification WHO/PQS/E007/VS01.5 [PQSVS01]. This includes the usable range above. The areas within this range but outside the usable range are said to be **stabilizable** or **usable if stabilized**.

Unusable Voltage: Voltage outside the stabilizable range, either above or below it.

Interruption or service interruption: A period when the voltage is unusable. This definition differs from IEEE 1159, which defines an interruption as voltage less than 10% of the nominal voltage, or 24 V in Kenya and 23 V in Nigeria. For the purposes of assessing the total amount of time when equipment can be operated, there is little effective difference between the two definitions, as discussed in the *Voltage Distributions* section. However, voltage varying around the 110 V threshold led to many short interruptions, as discussed in the *Interruptions* section.

Overvoltage: A period when the RMS mains voltage increases to more than 110% of its nominal value for more than 1 continuous minute, or greater than 264 V for Kenya and 253 V for Nigeria. This definition matches IEEE 1159. Overvoltage may be stabilizable or unusable.

Undervoltage: A period when the RMS mains voltage decreases to less than 90% of its nominal value for more than 1 continuous minute, or less than 216 V for Kenya and 207 V for Nigeria. Undervoltage may be stabilizable or unusable.

Voltage sag: A period when the RMS mains voltage decreases to less than 90% of its nominal value for less than 1 continuous minute.

Voltage swell: A period when the RMS mains voltage increases to more than 110% of its nominal value for less than 1 continuous minute.

Data outage: A period when data on power quality were not received for more than 30 continuous minutes. Examples of conditions that could cause data outages are extended interruptions that exceeded the monitoring equipment's battery charge and equipment failure.

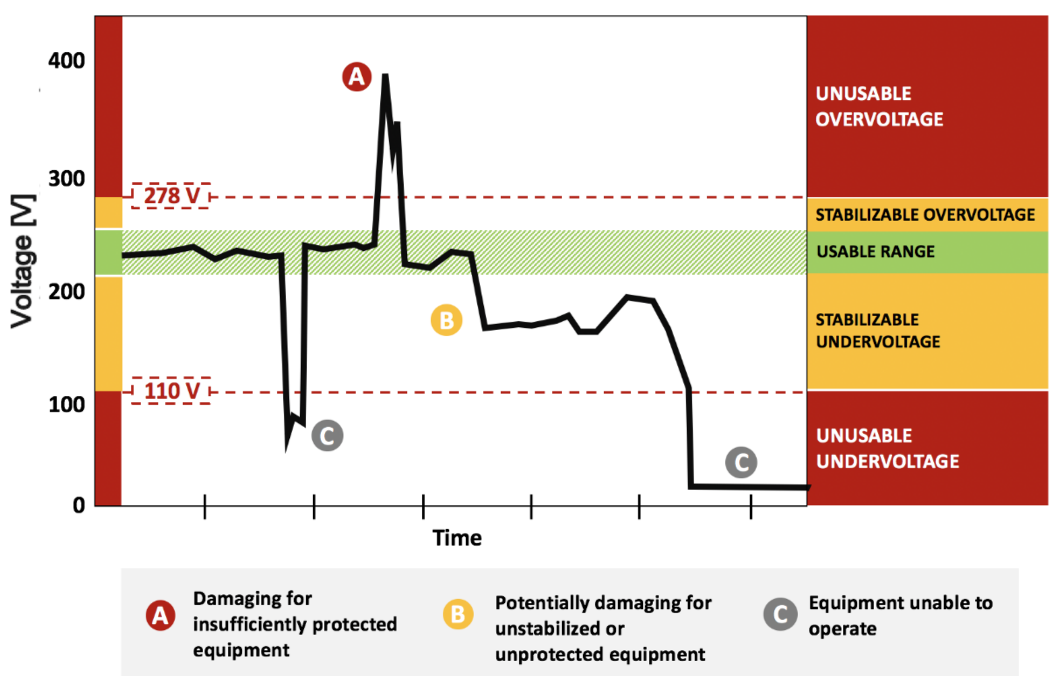


Figure 3: Simulated plot of voltage versus time to illustrate voltage range definitions.

4 Methodology

We gathered data on line voltage and frequency at the outlet level in 210 health facilities in Kenya and 93 health facilities in Nigeria over an 18-month period to understand the impact of power quality and availability on the operation of medical equipment. Our team installed vaccine refrigerators that transmitted data on power conditions as part of their routine self-monitoring process, to provide a reliable source of power data for analysis. Details on where and how we collected the data, as well as data reliability, are provided in this section.

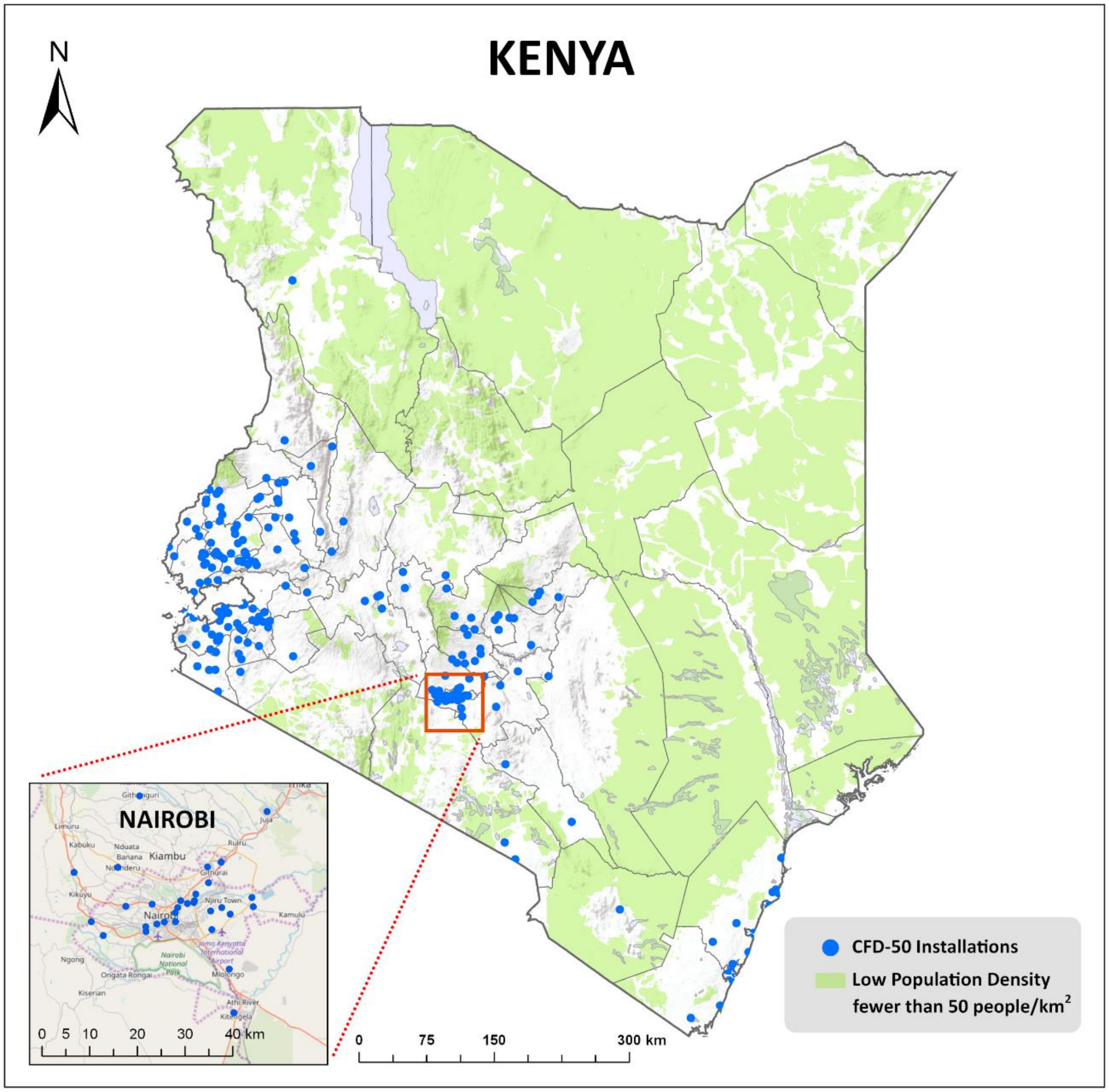


Figure 4: Locations of 210 devices in 36 counties in Kenya where power data were collected[14].

4.1 Where the Data Were Collected

Data were collected using WHO–prequalified mains-powered vaccine cold chain equipment (CCE) with integrated monitoring systems installed in health facilities in Kenya and Nigeria. Our team collaborated on the design of the devices used in the study. In Kenya, 210 devices were installed in 36 counties in collaboration with the National

[14] Population density geographic information system (GIS) data from [WorldPop], county/state mapping from [openAFRICA], with additional mapping data from [Esri] and [OpenStreet].

Vaccines and Immunization Program (NVIP), with 176 devices purchased by the Government of Kenya and the remainder purchased by GGF. Most devices were located in and around the major population centers in the Southwest, Southeast, and Nairobi and its surrounding area. Of the 210 devices, 176 were deployed at the health facility level, 33 at the subcounty level (i.e., hospitals and vaccine stores), and 1 device at a major vaccine depot. See Figure 4 for a map of device locations within Kenya.

In Nigeria, 93 devices were installed in 8 states and the Federal Capital Territory in collaboration with the National Primary Health Care Development Agency (NPHCDA), with all devices purchased by GGF. Approximately 10 devices were in each region. Of the total, 51 were deployed at the primary health care (PHC) facility level, 25 in hospitals, and 17 at the Local Government Area (LGA) or state cold store levels. See Figure 5 for a map of device locations within Nigeria.

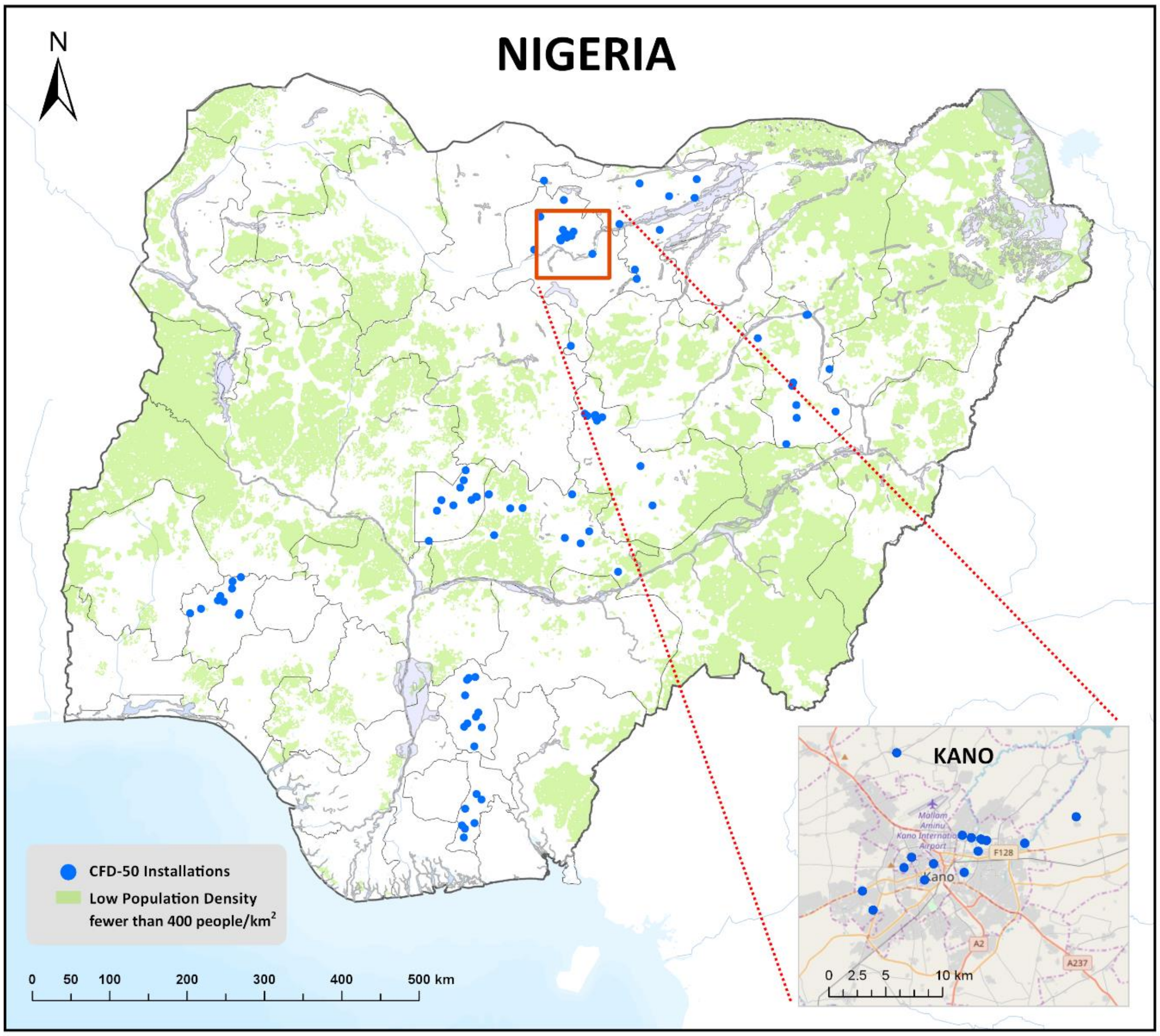


Figure 5: Locations of 93 facilities in the FCT and eight states in Nigeria where power data were collected.

The study took place over a nearly 18-month period from March 9, 2018 to August 31, 2019. Data collection began as devices were installed. As of August, 2019, all devices had been installed and had reported power data for at least 1.5 continuous months, with an average of 10 months of data reported per device in each country over the 18-month period. In aggregate across all devices, we collected 67,469 days of power data in Kenyan health facilities and 28,995 days of power data in Nigerian health facilities.

We focused on power availability at the facility outlet level as measured by each device. Thus, we evaluated conditions experienced by equipment installed at facilities. We did not evaluate the performance of the national power grid and in most cases are unable to determine whether an interruption or other voltage event (i.e., overvoltage, undervoltage, voltage sag, or voltage swell) was caused by problems with the electrical grid, local facility wiring, or both.

Some facilities were connected to the national power grid exclusively, some operated from a generator only, and others operated with a mixture of grid and generator power. As it is difficult to determine from the devices' reported data alone whether a facility was operating on generator power or grid power, in this analysis we do not differentiate among the three possible configurations. However, in the *Frequency* section of this paper, we do discuss frequency variability that is believed to be associated with generator-powered facilities.

4.2 How the Data Were Collected

The CFD-50 MetaFridge is a 50-L vaccine refrigerator manufactured by Qingdao Aucma Global Medical Co., Ltd., that incorporates an integrated WHO–prequalified PQS extended-range voltage stabilizer and an integrated performance monitoring system. This device's onboard monitoring system uses cellular network connectivity to relay telemetry data on vaccine chamber temperatures, refrigeration performance, and power to a remote database. While the primary purpose of these data is to help Ministries of Health maintain the integrity of vaccines stored in each device and inform future improvements to the refrigerator design, they also provide a window into power availability and quality at the facilities where a device is installed.

In each device, voltage is measured with a resistive divider sized so that RMS voltages up to 1662 V can be measured by the analog-to-digital converter (ADC) without distortion. Each of the two resistors has a 1% tolerance, meaning that the worst-case error for the voltage measurement is approximately 2%. The ADC has a gain error specification of ±4%. Offsets are nulled with a digital high-pass filter. Voltage and current are sampled at a rate of 1 kHz and converted to digital values with 24-bit resolution. The device uses these values to compute RMS mains voltage and frequency at 10-second intervals. Short-term spikes such as those caused by lightning are not reported.

In addition to the data, in-person and telephone communication with staff in a number of the health facilities studied provided important context in understanding the equipment-related challenges faced by staff in these facilities. We learned of the existence of generators, but not necessarily how often they are operated. In some instances, we also learned of facility wiring issues or reported problems with the power grid in the area.

4.3 Data Collection Reliability

In each device, the monitoring and telemetry systems are powered by an onboard backup battery to permit continuous operation during mains power interruptions outside of the CFD-50 device's acceptable input voltage range of 82 V to 290 V. While operating on backup battery power, the device's electronics continue to sample at a 10-second interval for about 33 hours. Then the device enters a low-power mode, waking every 10 minutes to briefly sample power (and temperature) values. When operating in this low-power mode, the device can continue to monitor voltage for up to 14 days before the battery is exhausted. Because the device's acceptable input voltage range (82 V to 290 V) is wider than the range that is usable with stabilization (110 V to 278 V), it is able to monitor voltage through some multi-week interruptions.

Across all 303 devices from March 2018 to August 2019, the proportion of time devices reported reliable data connectivity (defined as portion of time with no data outages) was 96%. Causes for missing data include cellular connectivity interruptions or device / telemetry module malfunctions. Another is power interruptions that extended beyond the 2-week capacity of a device's onboard backup battery. Over the course of the study there were 45 such events that started with extended interruptions and cumulatively caused a 1% data loss.

To avoid overreporting the duration of service interruptions due to data outages, no reported interruption contains any data outage greater than 30 minutes. For example, an interruption with a 31-minute data outage in the middle would be reported as two separate, shorter interruptions due to lack of knowledge of the conditions during the data outage. Power availability calculations are based on the periods of time with reported data, and make no assumptions about power availability during the 4% of the study period for which there are no data.

5 Findings

We discuss our findings regarding power availability overall, and at the facility level. Next, we consider the temporal nature of interruptions and their potential impact on operation of medical equipment in health facilities. We also report on the technical details of voltage and frequency and their implications for keeping equipment operating properly and without damage. Finally, we examine regional variations of power availability and interruptions.

5.1 Availability of Usable Voltage

Equipment is designed to operate when supplied with power within specified ranges for voltage and frequency. The parameters vary by equipment and manufacturer, but it usually matches or exceeds the normal operating voltage defined by power quality standards such as IEEE Standard 1159 and IEC 50160: within 10% of the system's nominal voltage (the usable range). Voltage outside the useable range may cause equipment to malfunction or damage it through several mechanisms. Voltage stabilizers can extend the usable range and protect equipment.

Our analysis of voltage ranges that are usable with stabilization also applies to certain kinds of equipment that have wide input ranges. For example, the power supplies for laptop computers and mobile phones have worldwide power input capability; these are designed to accept any grid source with nominal voltage between 100 V and 240 V and frequency between 50 Hz and 60 Hz, which is approximately the same range as usable with stabilization.

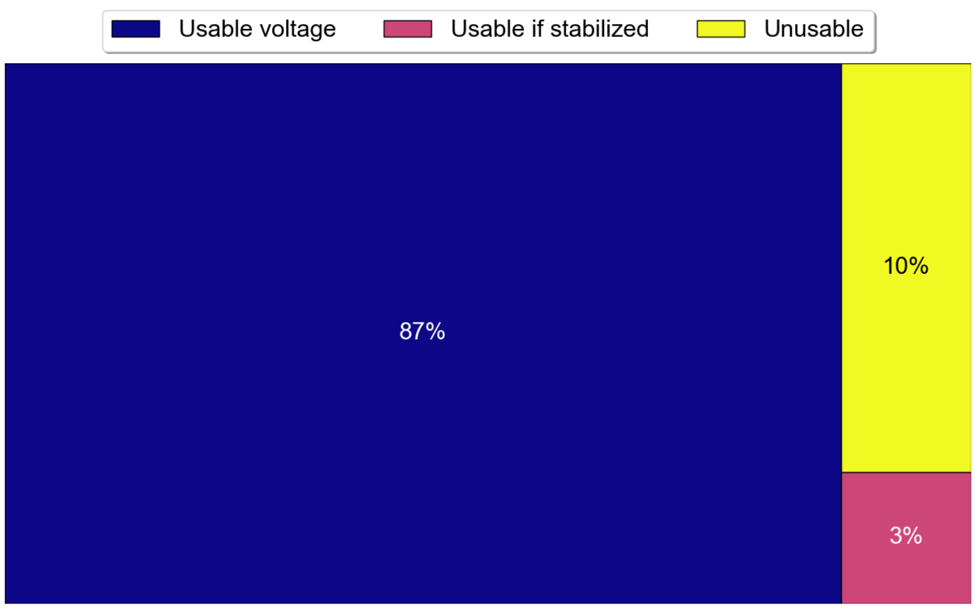


Figure 6: Percentage of time in each voltage range in Kenya.

Aggregate Usable Voltage

We separated the aggregate data for a country into three categories: usable, usable if stabilized, and unusable.

Figure 6 shows the data for Kenya. Devices in Kenya reported voltage within the usable range 87% of the time. Voltage was outside that range yet could be stabilized 3% of the time, and the remaining 10% was unusable during the study period. The total amount of time that voltage was usable if stabilized was a small fraction of the total, which suggests that voltage stabilizers may not be broadly needed in health facilities in Kenya. As we will see in the next section, however, individual facilities may benefit from stabilization.

Devices in Nigeria reported voltage within the usable range 27% of the time (see Figure 7). Voltage was stabilizable 15% of the time, which suggests that wider use of voltage stabilizers could improve equipment performance at health facilities in Nigeria. The remaining 58% of the time voltage was unusable during the study period.

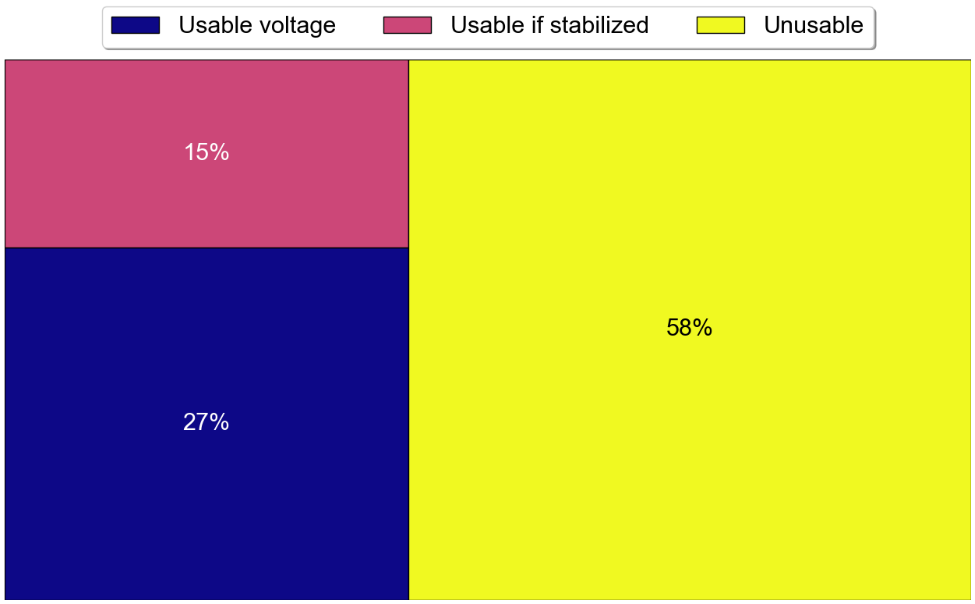


Figure 7: Percentage of time in each voltage range in Nigeria.

Usable line voltage at facilities

We next examine the availability of usable line voltage at the electrical outlet level in both countries.

Figure 8 shows the proportion of time during the study period devices in Kenyan facilities reported line voltage that was usable, with and without stabilization. Devices are grouped by percentage of time power was available. The yellow and blue bars show the impact of stabilization: yellow shows availability of usable voltage without stabilization, while blue shows availability with stabilization. With stabilization, 131 of the 210 devices (62% of devices) during the study period would have usable power at least 90% of the time; without stabilization, only 101 devices (48%) would be in this highest category. Stabilization also reduces the number of devices that would have poor power availability, shifting them into higher availability categories.

One possible evidence-based policy decision based on these data would be to focus distribution of voltage stabilizers to facilities that could benefit the most, e.g., for which the fraction of time with usable power would be most strongly increased by stabilization. Power availability data for each individual device are presented in Appendix B, showing the usable range and the amount that would be added with stabilization.

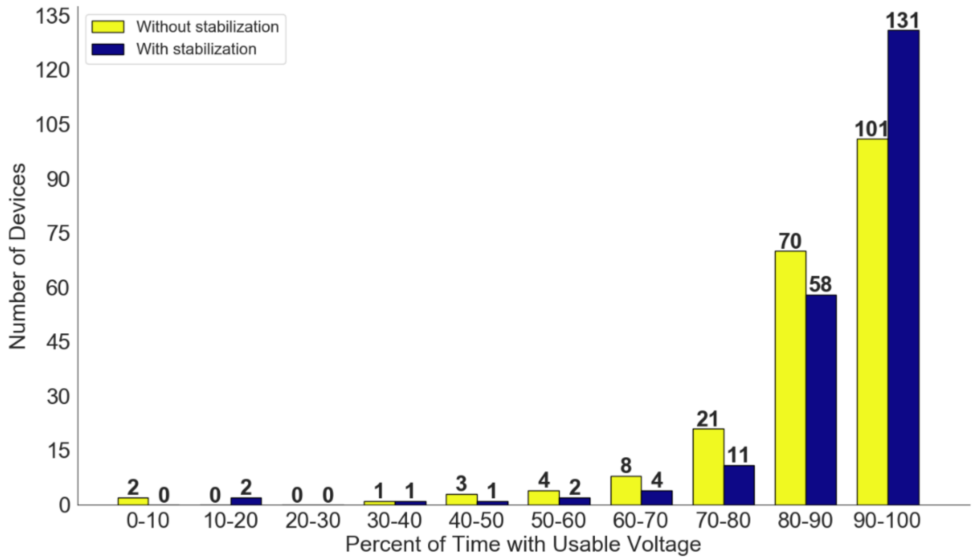


Figure 8: Number of devices in Kenya by percentage time of usable voltage, showing the impact of stabilization.

Figure 9 shows an analogous plot of devices in Nigerian facilities by percentage of time during the study period experiencing usable voltage. Without stabilization, 1 of 93 devices (1% of devices) would have usable voltage greater than 90% of the time, and 30 (32%) would have usable power less than 10% of the time. Using voltage stabilization would improve power availability for most devices. Even with stabilization, the majority of devices (66 devices, or 71% of the total) would have usable voltage less than half the time.

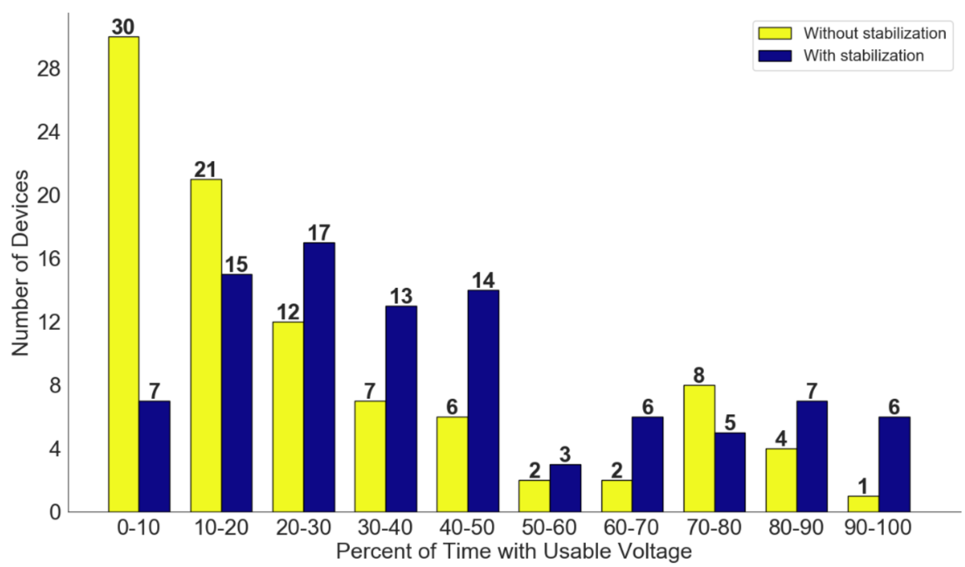


Figure 9: Number of devices in Nigeria by percentage time of usable voltage, showing the impact of stabilization.

5.2 Interruptions

Interruptions can occur between the electricity source and the device for many reasons. The electrical utility may experience sudden or long-term generation-capacity shortfalls, either systemwide or local. As a result, the utility may shed load on part of its system to balance energy supply and demand. Inclement weather, equipment failure, and accidents can also disrupt transmission and distribution systems. At the facility level, circuits may be overloaded, leading to tripped circuit breakers and/or damaged wiring. Facility staff may unplug the device to move it within the facility, or even to another facility.

In our analysis, an interruption is a period with unusable voltage: outside the 110 V to 278 V input range of a PQS extended voltage stabilizer. Because WHO-prequalified stabilizers are required to disconnect the load when the voltage is outside their input range, this choice mimics the behavior of a stabilized load. Equipment that does not have a stabilizer may experience periods where it cannot operate, for example due to undervoltage, but those periods are not captured here. Interruptions of over 14 continuous days may be underreported due to the device's onboard monitoring system battery being depleted and losing data connectivity.

The effect of an interruption on medical devices and other equipment found in an LMIC health facility depends on a number of factors. Even a momentary service interruption can disrupt equipment lacking an uninterruptible power supply (UPS). Depending on their design, systems with internal energy storage can tolerate interruptions of various lengths. Such storage can be from batteries (e.g., laptop computers, mobile phones in the process of charging) or thermal storage (e.g., WHO–prequalified ice-lined vaccine refrigerators can tolerate interruptions of multiple days).

Devices reported wide variation in the frequency, duration, and geographic distribution of interruptions in Kenya and Nigeria. In our analysis, we focus on continuous interruptions longer than 30 minutes and longer than 48 hours. Thirty minutes is a somewhat arbitrary value that represents an interruption that could be disruptive to health center operations. The longer period, 48 hours, is relevant to vaccine cold chain equipment (see sidebar, *Why Interruptions Matter*). Another point to note is that some facilities in the data set use gasoline- or diesel-powered generators, either as an alternative or a supplement to their electrical grid connection. In these cases, service interruptions were often regular and planned: generators were turned off daily as a fuel-saving measure or were only run as needed to power specific devices and equipment.

Durations and frequency of interruptions

Of the 256,823 interruptions logged over the course of this study across both countries, the vast majority were short: 77% persisted for fewer than 30 minutes. However, there were 1,610 instances (0.6% of the total) of interruptions 48 hours or longer. The remaining 22% of interruptions were between 30 minutes and 48 hours long.

Figure 10 shows the relative distribution of interruption durations in Kenya, demonstrating the large number of interruptions less than 48 hours long as well as the existence of multi-day interruptions. To better show the structure of the distribution, interruptions shorter than 30 minutes have been excluded from the plot; the plot contains only the 14% of interruptions in Kenya that were longer than 30 minutes. The x-axis bins represent the duration of the recorded interruption, and the y-axis represents the normalized counts in each bin, thus the relative frequency of occurrence (normalized so that the sum of the bins is equal to 1). The upper plot shows the counts on a linear scale, whereas the lower plot shows the counts on a logarithmic scale to highlight the interruptions longer than 48 hours (465 instances, or 0.3% of the total for Kenya). While it is difficult to visually count instances in the "long tail," there were 108 instances of interruptions persisting in excess of 7 continuous days.

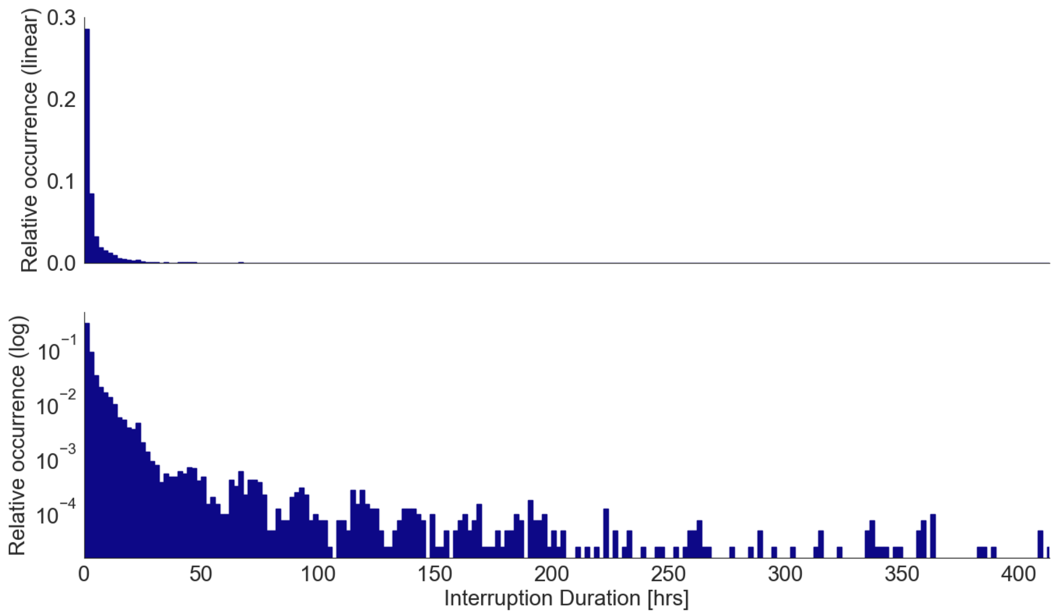


Figure 10: Interruptions greater than 30 minutes in Kenya, as reported by devices during the study period. Upper graph shows the relative fraction of occurrences on a linear scale; the lower graph shows them on a logarithmic scale. Bin width is set to 2 hours.

Quantile	Interruption Length, hours	Interruption length, seconds
20%	0.0028	10
40%	0.0089	32
(median) 50%	0.0197	71
60%	0.0500	180
80%	0.2036	733
90%	0.9594	3,454
95%	2.5914	9,329
99%	15.9575	57,447

Table 1: Quantile statistics for interruptions reported in Kenya. The median interruption was 0.0197 hours (71 seconds) long.

Table 1 shows a few more statistics of interruption lengths. Note that 20% of the interruptions are 10 seconds long, or a single sample interval. Some of these 10-second interruptions are due to voltage dropping from the range that is usable with stabilization to close to zero volts, but the bulk (94% of them) are due to voltage dropping slightly under the 110 V threshold. Some devices reported periods of voltage near this lower threshold, occasionally dropping below it. Each such event is recorded as an interruption according to our definition, as mentioned above. Two example time series traces that caused a series of these rapid interruptions are in *Appendix A* as Figures 32 and 33.

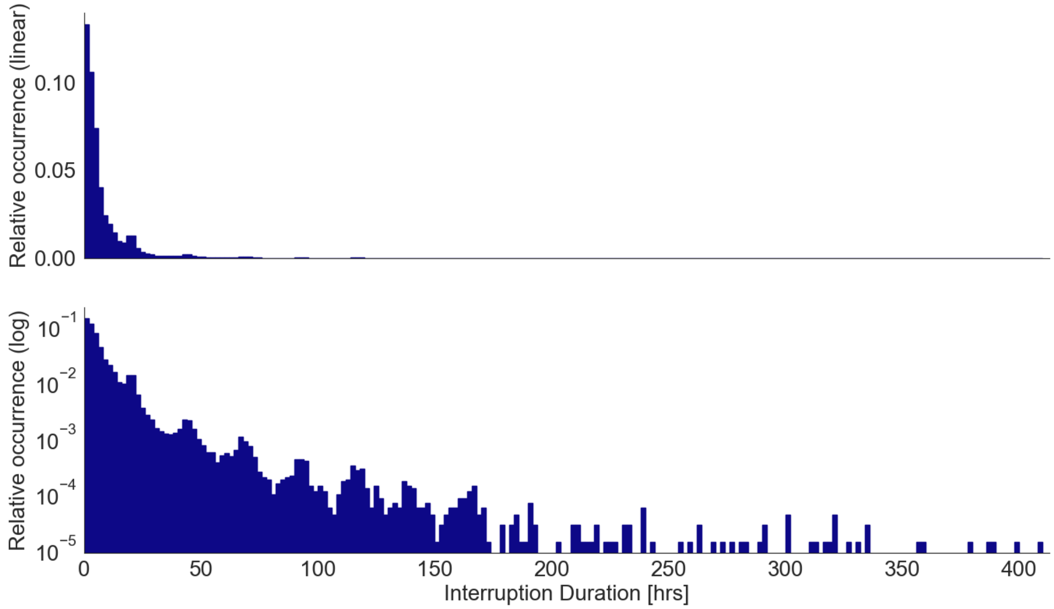


Figure 11: Interruptions greater than 30 minutes in Nigeria, as reported by devices during the study period. Upper graph shows the relative fraction of occurrences on a linear scale; the lower graph shows them on a logarithmic scale. Bin width is set to 2 hours.

Quantile	Interruption Length, hours	Interruption length, seconds
20%	0.0067	24
40%	0.0389	140
(median) 50%	0.1000	360
60%	0.2730	983
80%	3.5389	12,740
90%	8.2892	29,841
95%	17.5772	63,278
99%	51.5864	185,711

Table 2: Quantile statistics for interruptions reported in Nigeria. The median interruption was 0.1 hours (6 minutes) long.

The data reported by devices in facilities in Nigeria also showed many short interruptions and a significant quantity of long duration interruptions. Thirty-five percent (35%) of reported interruptions were longer than 30 minutes and are plotted in Figure 11. 1,145 instances (0.9%) were longer than 48 hours, and 80 were longer than 7 days. During the study period, there were also devices reporting *effective* interruptions in excess of one month due to extended undervoltage conditions. Table 2 shows summary statistics for interruption durations reported in Nigeria.

Interruptions by facility

While the previous section provided a country-specific view of all interruptions persisting for continuous periods, it is also instructive to examine the effects of interruption on a per-facility basis. If, for example, only a few facilities experienced the bulk of longer duration interruptions, an evidence-based intervention might focus only on improving conditions at those specific locations. However, interruptions were reported by devices operating throughout the bulk of facilities in the study.

Across all 210 devices in Kenya, during the full 18-month study period, there were 465 reported interruptions longer than 48 hours and 21,467 interruptions longer than 30 minutes. That averages to 2.5 interruptions per year longer than 48 hours for each device, and 118.0 interruptions per year longer than 30 minutes for each device. Figure 12 shows that these interruptions were not evenly distributed among devices; it categorizes them by the average number of interruptions per year. For example, on the left side of the figure, 32% of devices had no interruptions of 48 hours or longer, and 60% had more than 0 but less than 6.0 interruptions per year on average. The remaining 8% of devices reported between 6.0 and 42.6 interruptions longer than 48 hours per year.

The right side of Figure 12 provides a similar breakdown for all interruptions longer than 30 minutes. One percent (1%) of devices reported no interruptions of this length, and 60% in Kenya averaged between 0 and 120.0 interruptions longer than 30 minutes per year. The rest of the devices averaged more than 120.0 30-minute or longer interruptions. One device, or 0.5% of the total, averaged more than 480.0: it averaged 537.4 interruptions per year. In summary, nearly all devices in Kenya reported interruptions longer than 30 minutes, and about two thirds (68%) reported interruptions longer than 48 hours.

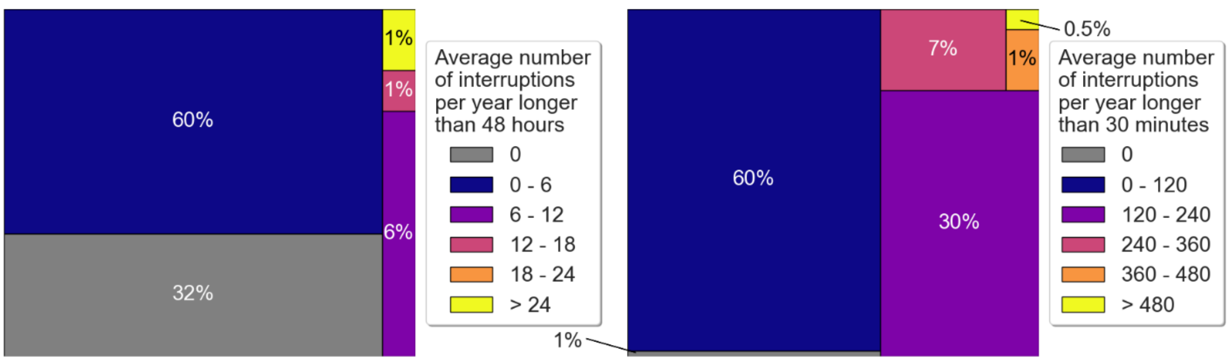
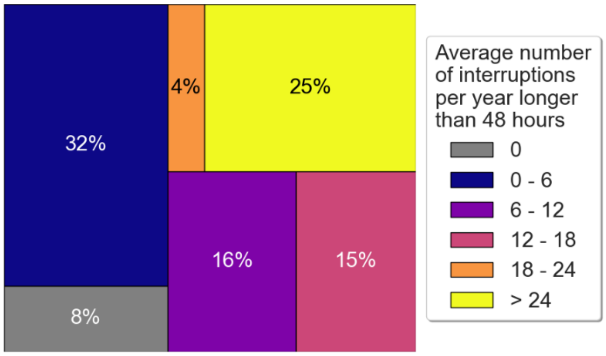


Figure 12: Percentage of devices that reported interruptions longer than 48 hours (left) and longer than 30 minutes (right) in Kenya.

Across all 93 devices in Nigeria, during the full 18-month study period, there were 1,145 reported interruptions longer than 48 hours and 36,549 interruptions longer than 30 minutes. That averages to 15.1 interruptions per year longer than 48 hours, and 453.1 interruptions per year longer than 30 minutes for each device. The left side of Figure 13 shows how interruptions 48 hours or longer are distributed between devices. Eight percent (8%) of devices had no interruptions 48 hours or longer, and 32% devices had more than 0 and less than 6.0 interruptions per year on average. The remaining 60% of devices averaged between 6.0 and 73.8 interruptions longer than 48 hours per year. The right side of Figure 13 shows the breakdown for devices in Nigeria with interruptions longer than 30 minutes. All devices reported some interruptions of this length, and 38% of devices reported an average of 480 or more such interruptions per year.



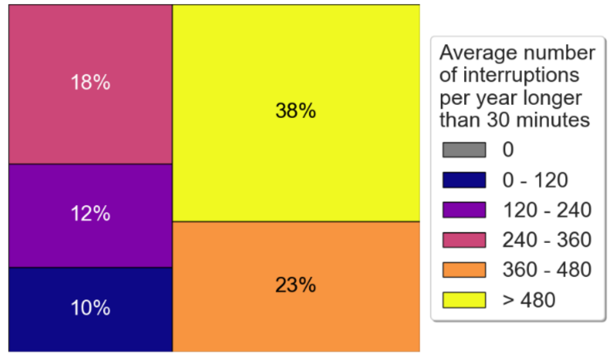


Figure 13: Percentage of devices that reported interruptions longer than 48 hours (left) and longer than 30 minutes (right) in Nigeria.

From in-person and telephone communications with the health facility staff at individual locations, we learned that some of the longer interruptions fell into two categories:

1. **Facilities using generators scheduled to operate intermittently**. Longer duration interruptions without generator runs were generally due to lack of fuel (or funds to procure fuel) or the generator breaking down.
2. **Facilities with electrical wiring issues**. Several locations had wall outlets that did not make sufficient reliable contact with the device's plug, resulting in service interruptions for those devices.

Why Interruptions Matter: Cold Chain Equipment Holdover Time

Mains-powered vaccine cold chain equipment (CCE) is an example of broadly deployed equipment that must continuously maintain performance through interruptions. This ability to maintain temperature in the safe 2–8 °C range for vaccines through interruptions is commonly referred to as *holdover time*. The WHO PQS standard for holdover time of intermittent-mains powered devices is broken into three categories [PQSRF03]:

Short: 20 Hours to 48 hours
Medium: 48 Hours to 120 hours
Long: 120 hours or more

Figure 12 and Figure 13 show that 68% of devices in Kenya and 92% of devices in Nigeria during the study period reported interruptions longer than 48 hours, indicating that a "short" holdover device (20 to 48 hours of holdover) would not be guaranteed to maintain safe storage chamber temperature in a substantial portion of these facilities. "Long" hold time devices provide additional vaccine safety here, where the percentage of facilities where devices reported interruptions longer than 120 hours drops to 44% for Kenya and 65% for Nigeria, indicating that increasing the holdover time from 48 to 120 hours would provide additional vaccine security for 24% of measured facilities in Kenya and 27% of measured facilities in Nigeria.

Short duration interruptions and return events

Data reported by devices during the study period also indicated that shorter duration interruptions (e.g., 30 minutes or less) tended to be clustered in time. Rather than manifest as isolated events, devices commonly reported such interruptions in close succession. For example, an overloaded circuit might disconnect from the electrical utility's distribution system. Subsequent attempts to restore service might fail if the overload has not been removed, leading to repeated interruptions. Regardless of the root cause, many types of medical devices and equipment could become inoperable in the face of rapid service interruption/restoration events over a multi-hour period.

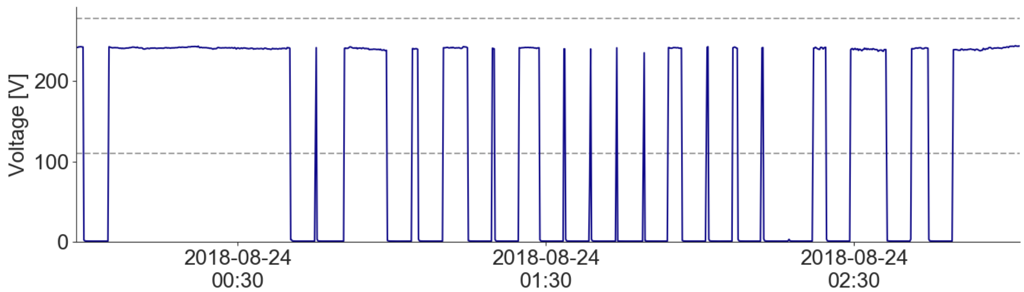


Figure 14: Time series plot of voltage reported by a device in a Kenyan facility. The voltage range usable with stabilization is between the horizontal dashed lines. Device K-026.

Even devices with integrated energy storage may not be operable, depending on the device and the rate of service interruptions/restorations and their respective durations. For example, a refrigeration device must typically run its compressor for longer than a few minutes to make a meaningful contribution to cooling. In addition, compressors are not designed to start and stop more than about 10 times per hour, ideally much less frequently than that.

Figure 14 shows an example of a reported series of interruptions experienced by a single device in a Kenyan facility. This plot shows that the service at the electrical outlet was interrupted and restored 21 times during a 3-hour period. In some instances, power was restored and persisted only for a few seconds before the next interruption.

5.3 Voltage Deviations from Nominal

Voltage sags and sustained undervoltage can potentially damage equipment through overheating. For devices and equipment to draw sufficient power in such circumstances, the amperage drawn must increase as input voltage decreases. Higher currents lead to greater resistive losses and heat is generated as an unwanted byproduct. Additionally, electric motors can lose torque and stall under such conditions, and a stalled electric motor draws large currents that can rapidly heat it. Overvoltage conditions also can cause some devices to draw higher currents or can break down insulating dielectrics or semiconductor components and permanently damage devices and equipment.

Voltage distributions

First, we explore the distribution of service voltage in detail across all Kenyan and Nigerian facilities for the entire study period. Figures 15 and 16 aggregate every data sample acquired, separating them into bins 0.1 V wide. Voltages less than the IEEE 1159 definition of interruption (24 V or 23 V, respectively) were omitted to show the structure of the rest of the distribution. These represent 9.9% of all voltage samples from Kenya and 58% of all samples from Nigeria. The plots were normalized so the bins sum to 1, representing 100%. Also shown on the plots are two voltage ranges: (a) usable voltage and (b) usable with stabilization.

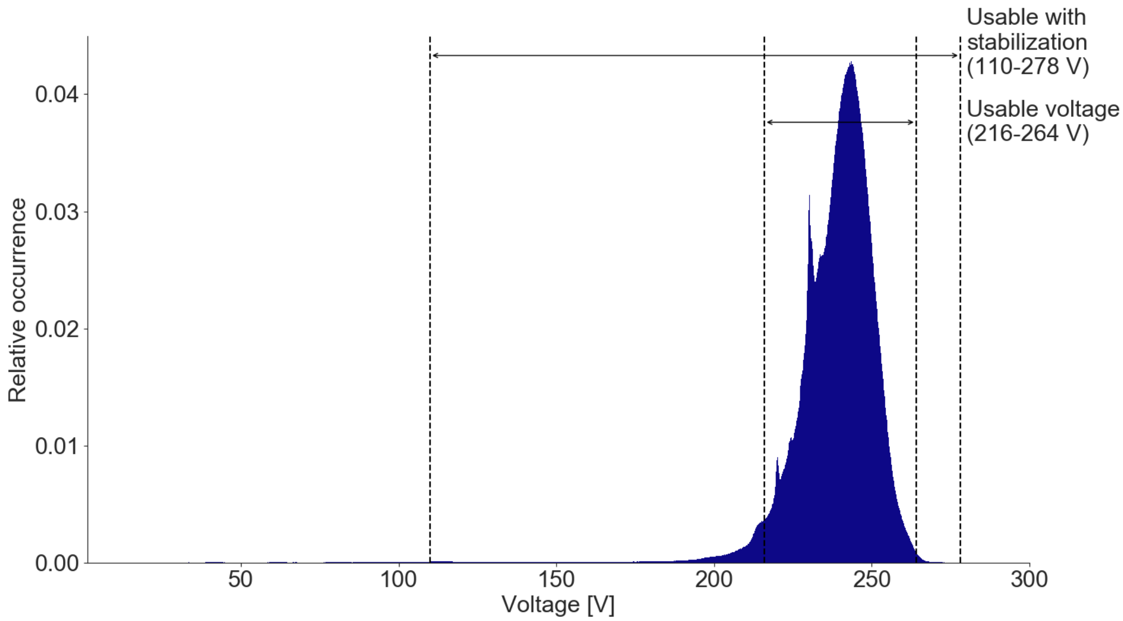


Figure 15: Line voltages reported by devices in Kenyan facilities during the study period (normalized to 1). Mean is 238.3 V; standard deviation is 16.0 V.

Figure 15 shows the distribution of voltages reported by devices in Kenyan facilities. As we saw above, for the majority of the time reported, the voltage at the outlet falls within 10% of nominal (usable) range. Also note the very small proportion of samples that are in the unusable range but greater than 24 V, 0.3% of the total. As we saw in the *Interruptions* section, many short-duration interruptions were a result of voltage samples that dropped slightly below the 110 V threshold. But because they are so much fewer than the 9.9% of samples that are less than 24 V, there is little difference between our definition of interruption and the definition used by IEEE 1159, at least in terms of total amount of time spent in interruptions. A few devices reported voltage profiles that departed dramatically from the aggregate results yet were not numerous enough to be visible in this plot. (The x-axis range is limited to 300 V for clarity; sustained severe overvoltages are addressed in the next section.)

The distribution of line voltages reported by devices in facilities in Nigeria is shown in Figure 16. The area of stabilizable undervoltage is apparent, as is a small amount of unstabilizable undervoltage above 23 V, representing 0.9% of all samples (compared to the 58% of samples that are less than 23 V).

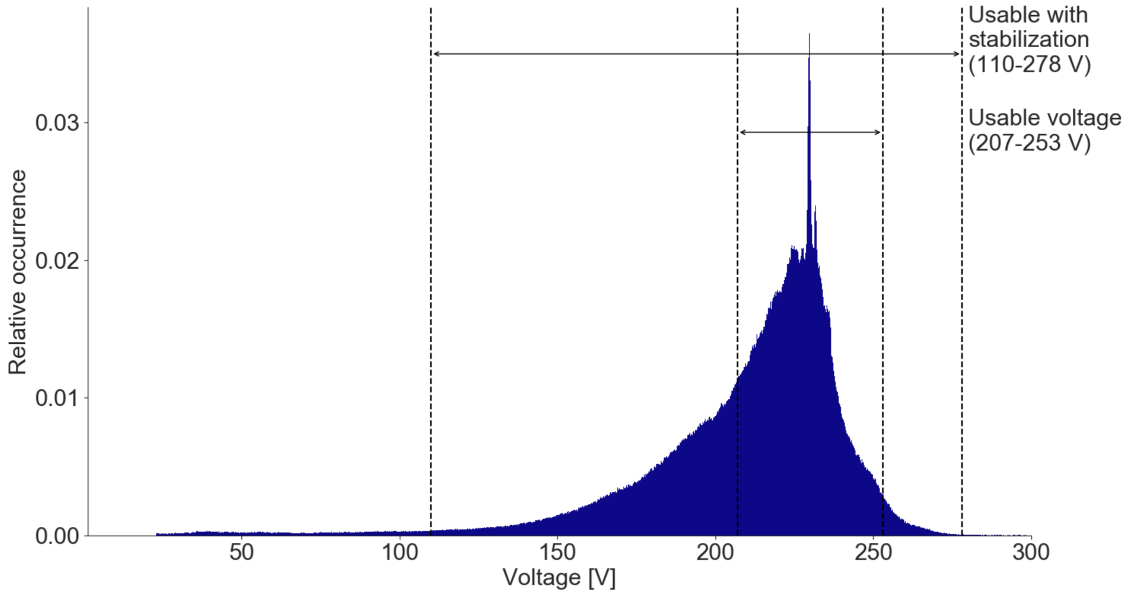


Figure 16: Line voltages reported by devices in Nigerian facilities during the study period (normalized to 1). Each x-axis bin represents 0.1 V. Mean is 209.9 V; standard deviation is 33.5 V.

Sustained overvoltage conditions

Over the course of the study, we recorded overvoltage events in both countries extending from a few minutes to several hours. In Kenya, 6 devices reported continuous events longer than 1 minute with voltages in excess of 350 V, and 3 devices reported events in excess of 450 V. Similarly, in Nigeria 9 devices reported voltages in excess of 350 V and 1 device reported voltage events in excess of 450 V.

Figure 17 contrasts a voltage trace that is near ideal with a sustained overvoltage condition. The purple trace is a plot of line voltage over the course of two days at an office in Nairobi, Kenya, that was not one of the health facilities involved in the study. Due to variations the utility's supply or in load on the system (whether in the building or the neighborhood), the voltage varies from 235 V to 249 V, or from -2% to +3.8% of nominal 240 V, a range that poses no challenges for typical equipment. The blue trace was reported by a different device in a Kenyan health facility during the same period; this device reported voltage in excess of 400 V for 28 continuous hours.

It is not clear what caused the sustained overvoltage conditions reported by these 15 devices in both countries. One potential cause of overvoltage can be a disconnected neutral wire in a three-phase system that uses each phase for independent single-phase equipment. If the loads on each phase are not identical, the phases will split the voltage unevenly: one experiences less than its normal amount of voltage and another experiences correspondingly more. Regardless of cause, these overvoltages are outside the input voltage range recommended for safe operation of most medical devices and equipment designed to operate with 230 V to 240 V nominal voltage.

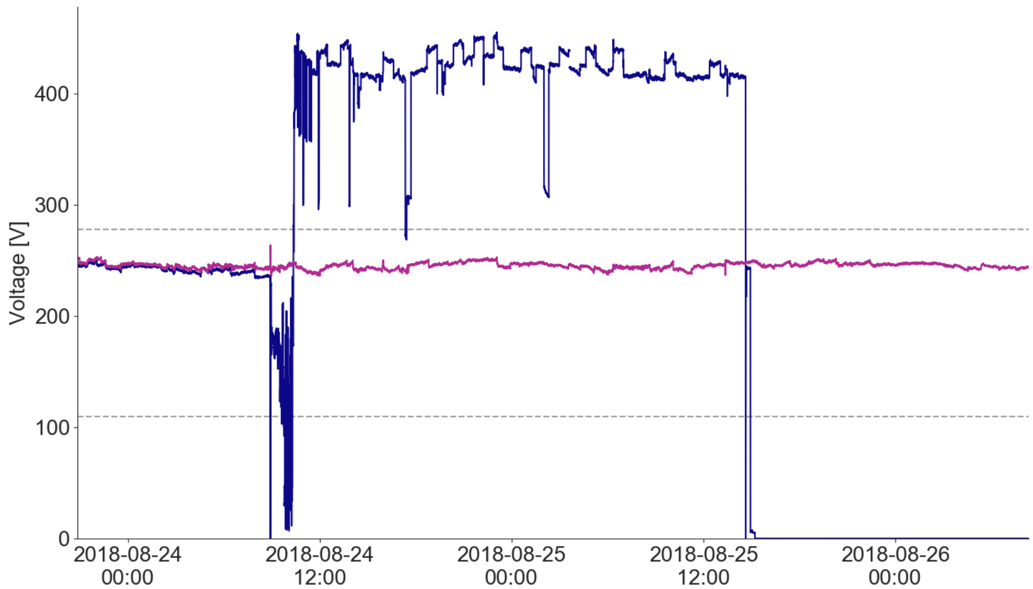


Figure 17: Voltage as a function of time during the study period for two devices in Kenya, contrasting usable voltage with a day-long overvoltage. The voltage range usable with stabilization is between the horizontal dashed lines. Blue trace is device K-117; the purple trace was from a device not in the study.

Undervoltage conditions

Because so many reported voltage samples were lower than nominal, it is no surprise that sustained undervoltage conditions were common and that at times they extended for many hours. This section contains examples that are representative of the different types of challenging undervoltages reported during the study period. An example period of undervoltage in Kenya is shown in Figure 18. The total duration of this event that contains multiple crossings of the border between stabilizable and unstabilizable undervoltage is approximately 20 hours. Some sustained undervoltage events have fairly steady voltages, like the middle portion of this example, but many also exhibit highly transient behavior.

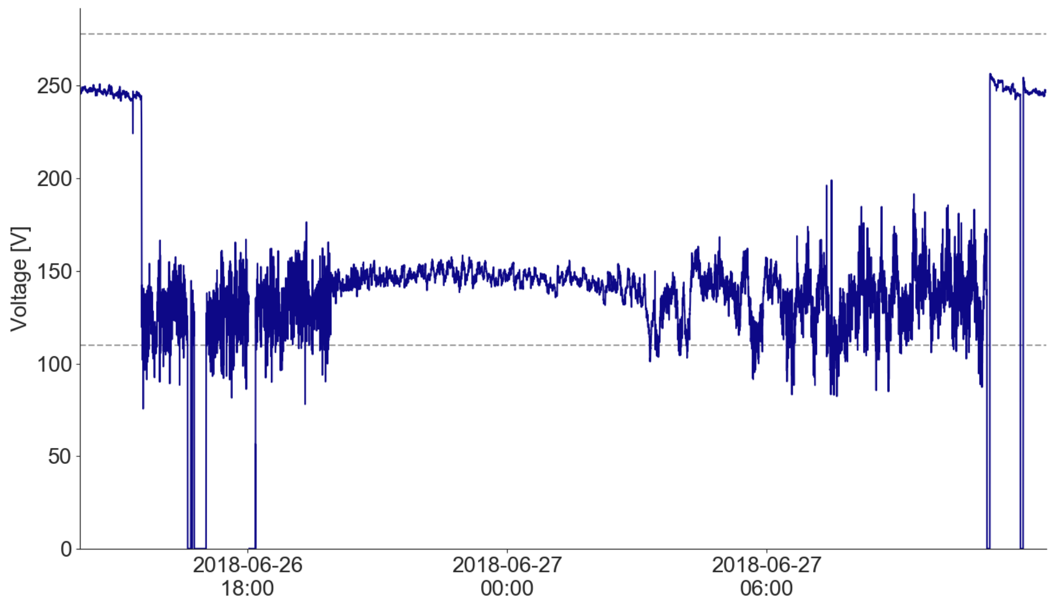


Figure 18: Sustained undervoltage in Kenya, device K-147.

One example of a longer undervoltage event with large line voltage variations reported by a device in Nigeria is shown in Figure 19. This facility is connected to the electrical grid, but also uses a backup generator. During the continuous 2.5-day period when reported line voltage departed from nominal voltage, the device reported seemingly random high and low voltage variations. These variations were mostly on time scales between 5 and 20 minutes long. The undervoltage conditions are prefaced and followed by line voltage varying only from approximately 220 V to 230 V (i.e., within the usable range of nominal voltage ±10%).

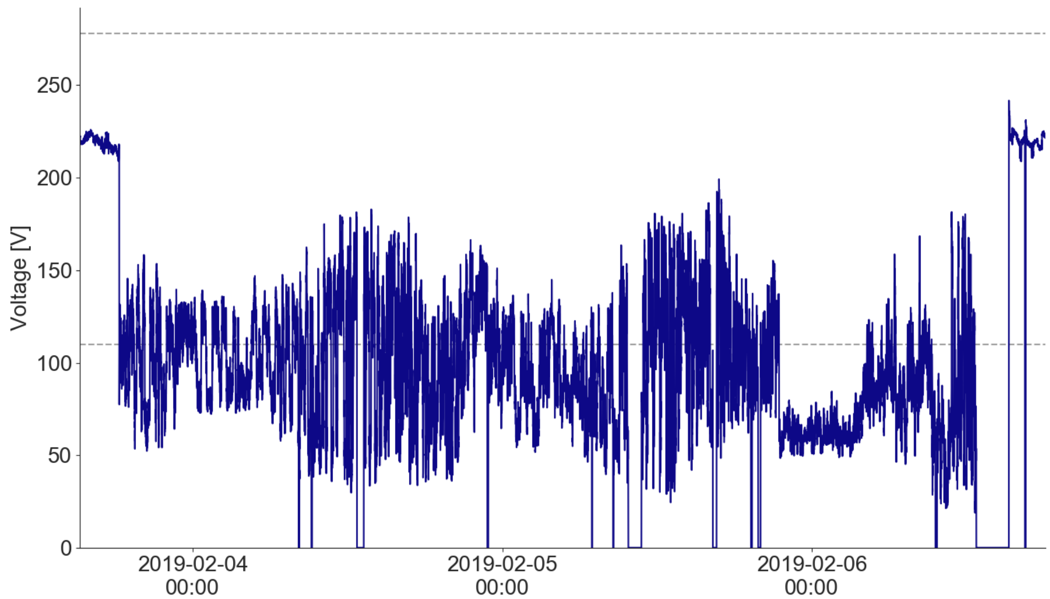


Figure 19: Highly transient undervoltage conditions in Nigeria, device N-058.

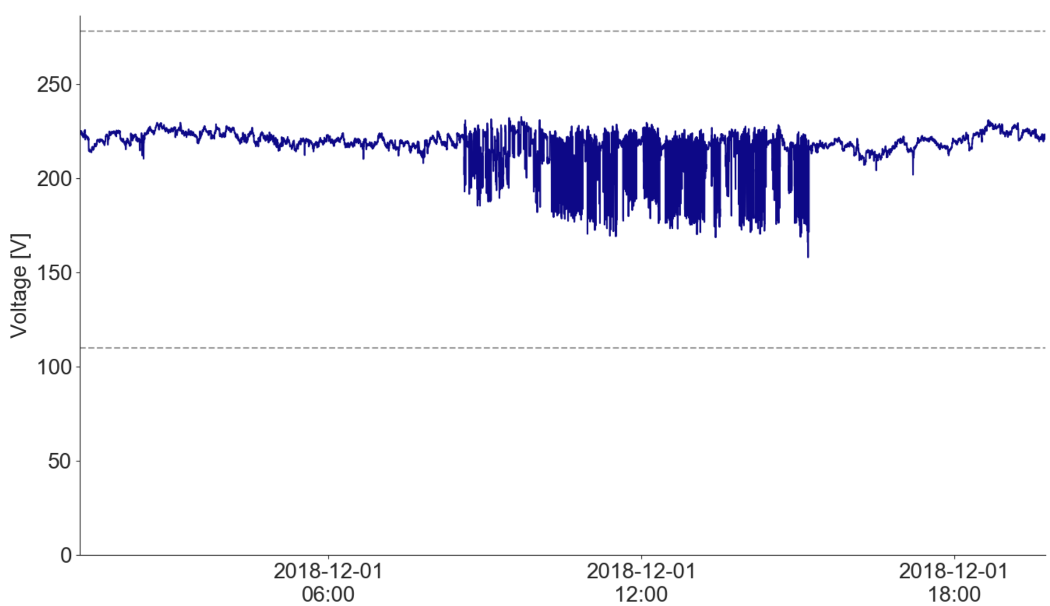


Figure 20: Transient undervoltage conditions in Kenya. During this multi-hour period, reported line voltage occasionally spiked by 50 V during 10-second intervals. An expanded view is shown in Figure 21. Device is K-172.

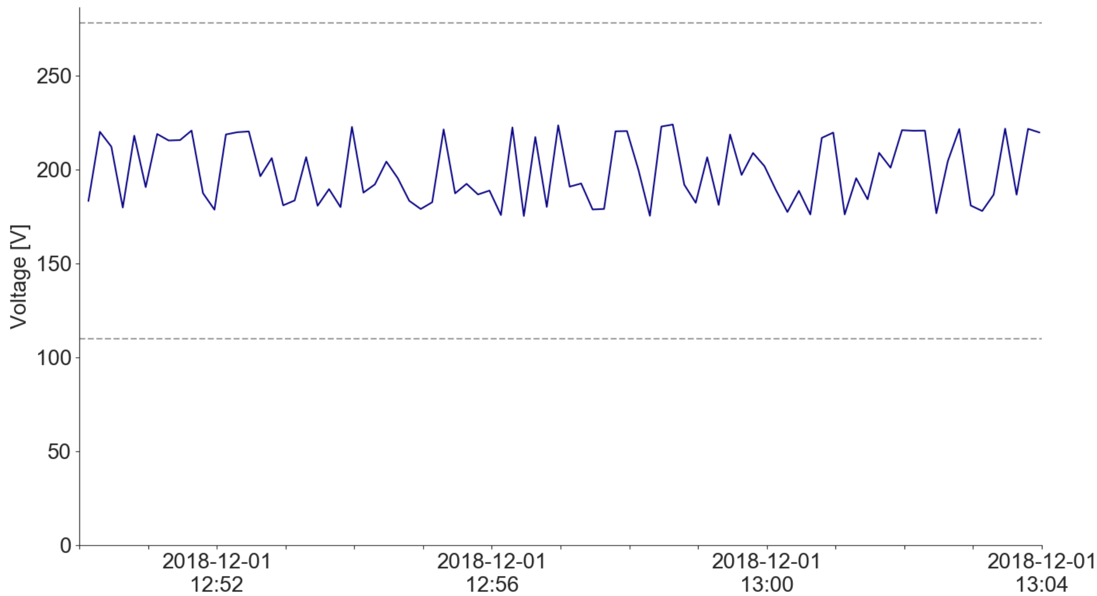


Figure 21: Transient undervoltage conditions in Kenya, expanded view of previous figure. Note the 50 V jumps and drops from one 10-second interval to the next.

Another example, this time from Kenya, is shown in Figure 20. Over the course of a few hours, the device reported line voltage variations ranging from approximately 170 V to 230 V. The 60 V difference between minimum and maximum reported line voltages is large; however, the larger challenge to voltage stabilizer design is that the line voltage variation often spiked by 50 V to 60 V within a 10-second interval, only to be followed by a similar 50 V to 60 V drop 10 seconds later. See Figure 21 for an expanded view of one such event. These variations within such a short time frame underline the importance of medical devices and equipment being capable of operating safely in such conditions, as well as WHO–prequalified voltage stabilizers being designed to help protect such devices and equipment. When experiencing transient undervoltage conditions, it may be prudent for devices, equipment, or their accompanying voltage stabilizers to disconnect from the line until relative stability is restored.

Voltage sags when loaded

Another type of issue observed is exemplified by the time-series plot shown in Figure 22. When this particular device in Kenya was not utilizing much power (i.e., low current draw), the line voltage was within 10% of nominal voltage. However, as the induction motor–based compressor in the device attempted to start, its current draw pulled the line voltage down, thus preventing proper compressor operation. From an electrical engineering standpoint, the source impedance of the power system appears to be high. Note that only two of the four reported voltage sag events in Figure 22 correspond to failed attempts to start the compressor. The causes of the other two reported voltage sags are unknown, but it is likely that other devices or equipment in the facility operating on the same electrical circuit were attempting to draw current and thus caused reduced line voltage.

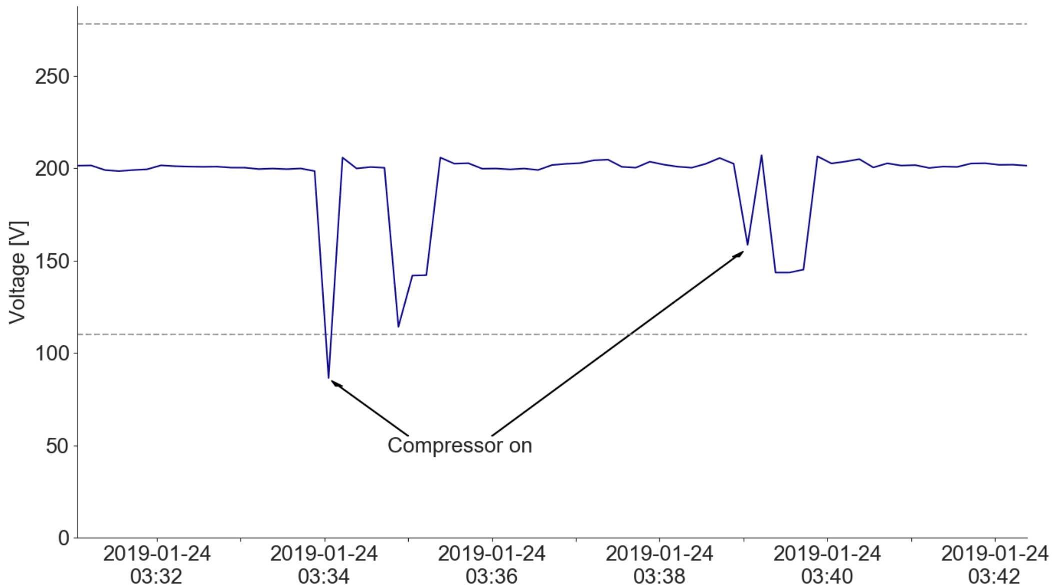


Figure 22: High source impedance, device K-080.

Some potential causes of a high impedance condition are a loose connection in the facility's wiring, wires sized too small for the load, similar wiring problems in the electrical utility's distribution system, or a poorly tuned generator. The village in which this health facility is located experienced service interruptions, undervoltage conditions, and occasional voltage swell events that were reportedly due to a distribution transformer problem, though we were not able to confirm the exact cause. However, an investigation at a different facility in Kenya in which the installed device had reported similar data revealed the root cause as a faulty outlet—the electrical connection was poor, and in addition to voltage sags electrical arcing had damaged both the outlet and the device's plug. While not common, this condition can prevent certain kinds of equipment from operating properly.

5.4 Line Frequency

In an AC electrical power system, the line voltage frequency is an important contributor to overall power quality. Many of the world's electrical power systems utilize a nominal frequency of 50 cycles per second, or 50 Hz. Countries in North America, Central America, northern South America, the Caribbean, Korea, and western Japan utilize 60 Hz. The electronic power supplies in personal computers and other computerized equipment are tolerant of frequency variations, and modern power supplies for common household appliances and equipment are usually designed to operate worldwide over at least a range of 45 Hz to 65 Hz.

Many electric motors base their operational speed on frequency: as the frequency changes, so do the motor's operating characteristics. If the frequency is too high or too low, the motor can overheat through different mechanisms, and if the torque it develops drops too low it can stall. For priority medical devices and equipment, the acceptable line voltage frequency range depends on the product's design. For example, some compressors used in vaccine refrigerators can operate at both 50 Hz and 60 Hz nominal frequencies, whereas other motors are designed for 50 Hz or 60 Hz, but not both.

Kenya

The line frequencies reported by devices in Kenyan facilities during the study period are plotted in Figure 23. Within the complete data set reported by these 210 devices in Kenya, only samples with voltages within the PQS extended stabilization range of 110 V to 278 V were plotted. The x-axis of this histogram represents bins with a width of 0.05 Hz, and the corresponding occurrence values are normalized with all bins summing to 1.

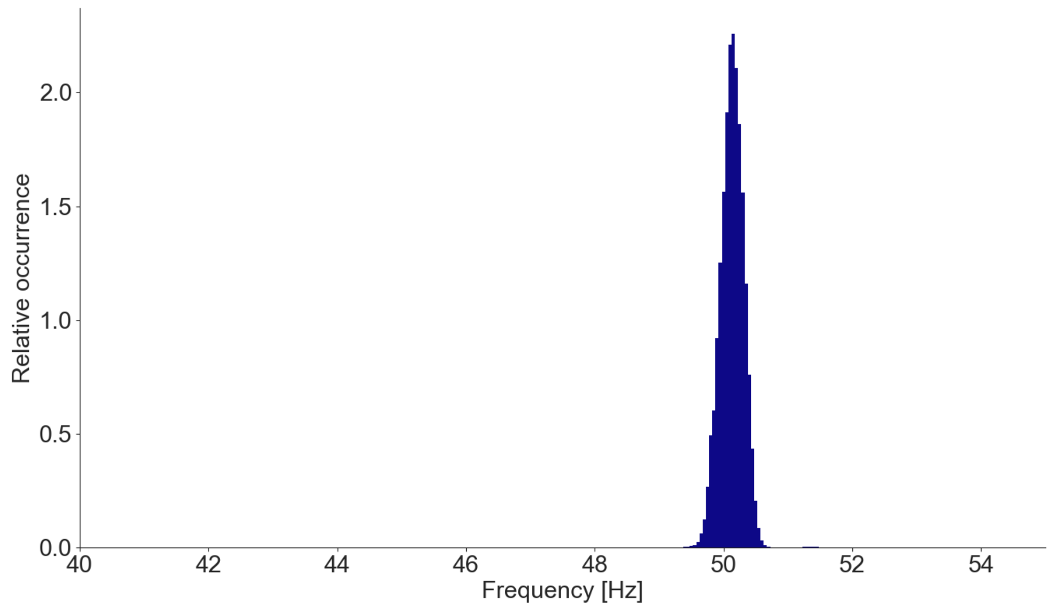


Figure 23: Distribution of line frequency in Kenya, as reported by devices during the study period.

The distribution is narrow and centered close to the nominal frequency of 50 Hz with a mean of 50.1 Hz and standard deviation of 0.64 Hz. Frequency was reported outside the range 45 Hz to 55 Hz 0.1% of the time. From communications with many of the Kenyan facilities, we know that most are grid connected and do not use generators. The electrical distribution system's frequency, as reported by these devices, appears fairly uniform across facilities, leading us to conclude that (a) generators are not used by these facilities and (b) the electrical utility, KPLC, appears to have regulated system frequency well during the study period and in these specific locations of the country.

Nigeria

A similar distribution for data samples reported by devices in Nigerian facilities is shown in Figure 24; it has a mean of 50.0 Hz and standard deviation of 1.9 Hz. The narrow peak at 49.9 Hz is largely due to a single facility, a hospital with a generator that runs at a very constant frequency, though not always 100% of the time. Figure 24 also shows a smaller yet still noteworthy peak of reported samples around 46 Hz to 47 Hz. Though small relative to the main peak, it represents a significant amount of operational time and tends to be concentrated by facility. That is, devices in most Nigerian facilities reported line frequencies close to the nominal frequency of 50 Hz nearly all of the time during the study period, whereas devices in some facilities often reported frequency far lower than the nominal frequency. Frequency was reported outside the range 45 Hz to 55 Hz 2.2% of the time.

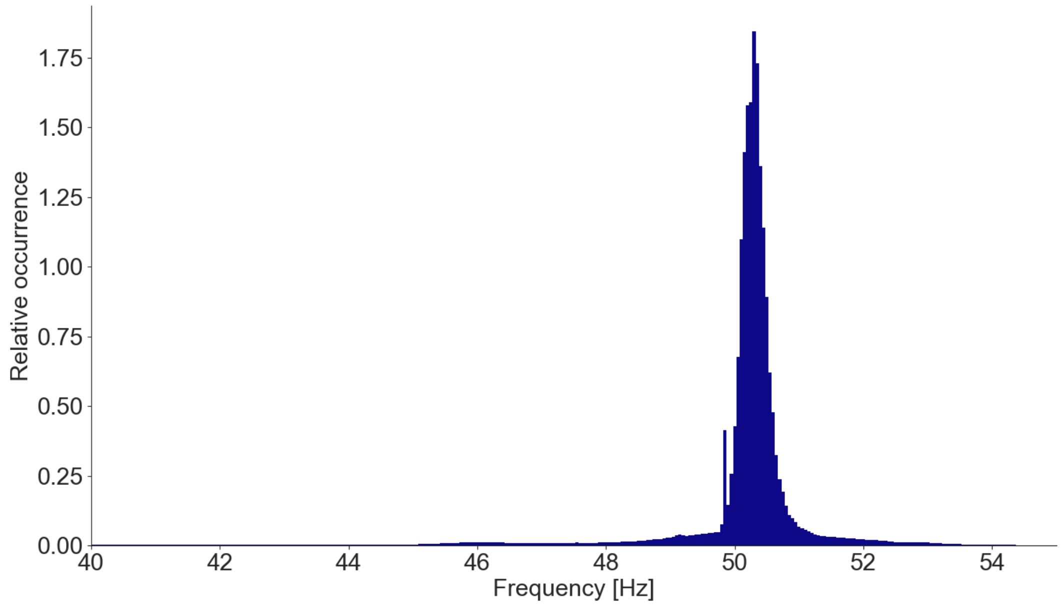


Figure 24: Distribution of line frequency in Nigeria, as reported by devices during the study period.

Generators

Based on information collected from health facility staff, numerous Nigerian facilities in this study utilized facility generators. In the Kenyan facilities in this study, generator existence and use were quite limited. We learned of generator sites via visits or phone calls to the facilities, but we do not always know whether a location was using a generator all the time, as back-up for the grid, or not at all. However, it is likely that many of the frequency excursions beyond 49 Hz to 51 Hz are due to use of generators, as facilities noted to have frequency excursions were in many cases verified via phone or in-person visit to be using a generator. Generators must be well maintained to yield safe and reliable power during planned or unplanned service interruptions. Frequency and line voltage are likely to vary from normal parameters in a poorly maintained or overloaded generator.

Another characteristic of a poorly tuned or overloaded generator is that it may operate within acceptable power parameters without a load but may be unable to maintain that same performance standard when loaded. Figure 25 shows an example of the frequency dropping from 63.5 Hz to about 50 Hz when the device's compressor is started. About three-quarters of the way through the time period shown, the load on the generator increases again and frequency drops to approximately 41.5 Hz.

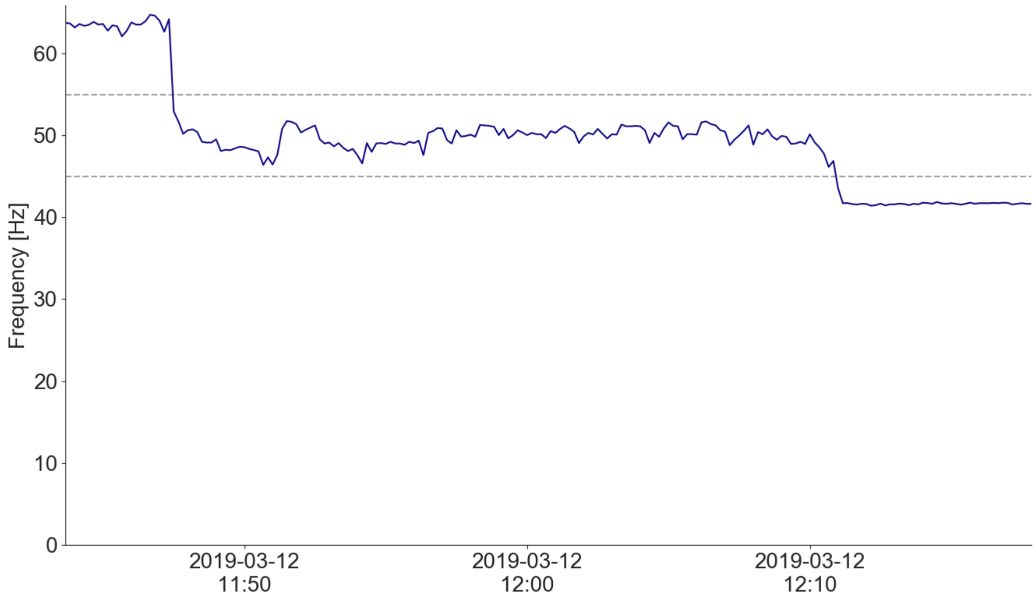


Figure 25: Generator frequency dropping under load. Horizontal dashed lines at 45 Hz and 55 Hz. Device is N-089.

Implications

Line frequency variations can stress or damage various kinds of priority medical devices and equipment, particularly those that use electric pumps and motors. Such devices and equipment designed for use in LMIC health facilities would benefit from protective features that disconnect the entire device, or at least the more sensitive components of it, from mains power when the mains frequency extends into potentially damaging territory, beyond 10% from nominal frequency. One design challenge associated with a disconnect is communicating to the end user why the equipment is no longer operating. Other less sophisticated devices and equipment such as incandescent lamps operate successfully at 30 Hz, so end users may see a lamp operating and conclude the medical devices and equipment, which have shut down due to frequency protection, are broken.

Voltage stabilizers have the potential to improve the power quality and protect equipment. As typical voltage stabilizers (e.g., transformers) are not able to modify frequency, part of this protection should be to disconnect the load when the mains frequency falls outside of a range for typical loads necessary to safely and reliably operate equipment.

5.5 Geographic Distribution

Data reported during the study period by devices in Kenya and Nigeria were also aggregated by administrative regions to examine regional variability and trends. In Kenya, devices were grouped at the county level. However, the number of devices per county varied considerably, from 1 device in each of 7 counties to 27 in Nairobi County and 26 in Homa Bay County. For this reason, it is important not to place too much weight on the results for an individual county. However, many counties are adjacent, and there appear to be trends across counties. If more devices are installed in the future, these trends may become better defined. In Nigeria, devices were installed in 8 states and the Federal Capitol Territory of Abuja. Each region had 9 or 10 devices installed, except Kano State, which had 16.

Just as it is difficult to determine the cause of power quality problems from measurements at the facility electrical outlet, it is difficult to draw conclusions about the causes of wider scale trends. In particular, the organization of the national electrical grid does not necessarily correspond to governmental boundaries, meaning that electrical grid problems might impact only part of a single administrative region or multiple administrative regions at the same time. Furthermore, health facilities in a particular area could share similar resource challenges independent from grid availability.

Nonetheless, a geographic perspective on power availability and interruptions can help inform an understanding of general trends of regional power conditions. Understanding these trends can be valuable to identify whether there are particularly challenging areas where specific equipment types should be deployed, or if all regions have similar power availability profiles.

Geographic Availability of Usable Voltage

Figures 26 through 29 map average power availability and multi-day interruptions in the counties in Kenya and states in Nigeria where devices reported data during the study period. The average power availability across devices within each county in Kenya is shown in Figure 26. As in the *Availability of Usable Voltage* section, availability is calculated as a percentage of time that devices reported voltage within the usable range during the study. The average percentage of time of usable voltage is indicated by the color of the county on the map. The data and number of devices in each county are shown in Table 3. Availability of usable voltage in Kenyan counties ranged from a minimum of 76% to over 96%[15]. From these data we can also see that devices in the southeastern part of the country reported relatively higher power availability, whereas devices in the central and western counties reported less availability, except for urban Kisumu and Nairobi Counties. Table 3 also shows the effect of voltage stabilization on power availability for each county in Kenya, where we see slightly increased availability across most counties included in the study.

[15] While data reported in one county (Taita Taveta) indicated 100% power availability, only one device was located in this particular county, so this is not representative of the county as a whole.

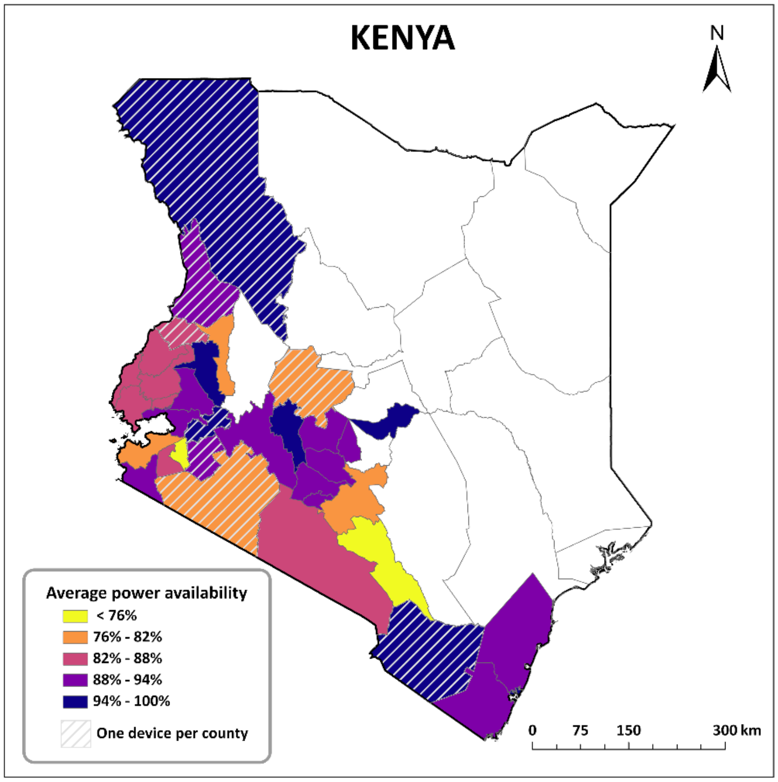


Figure 26: Average availability of usable voltage by county, as reported by devices in Kenya during the study period (not measured in counties with no color coding). Cross hatching denotes counties with a single device.

County	Number of Devices	Usable with Stabilization (110 V - 278 V)		Usable Range (216 V - 264 V)	
		Average Power Availability %	Average Interruptions > 48 hours per device year	Average Power Availability %	Average Interruptions > 48 hours per device year
Bomet County	1	94.0	1.3	93.9	1.3
Bungoma County	8	90.1	2.7	86.6	3.0
Busia County	7	87.6	2.2	83.2	5.4
Elgeyo Marakwet County	5	84.4	7.1	81.5	7.4
Embu County	2	95.4	1.3	94.9	1.3
Homa Bay County	26	81.0	4.9	78.7	6.7
Kajiado County	3	93.5	1.1	83.0	2.6
Kakamega County	20	89.2	2.0	87.0	2.5
Kericho County	1	95.0	0.0	94.8	0
Kiambu County	7	94.2	1.8	88.7	2.9
Kilifi County	11	94.9	1.2	90.4	1.6
Kirinyaga County	4	94.4	1.0	93.8	1.3
Kisii County	7	86.8	1.0	85.5	3.5
Kisumu County	4	96.2	0.3	93.7	1.0
Kwale County	2	90.6	1.6	90.0	1.6
Laikipia County	1	77.6	10.8	77.3	10.8
Machakos County	6	82.0	7.6	79.3	8.5
Makueni County	2	75.8	3.6	75.7	3.6
Migori County	5	89.7	1.6	88.6	2.7
Mombasa County	3	97.7	0.4	96.9	1.2
Murang'a County	7	93.6	2.5	89.6	2.7
Nairobi County	27	94.3	1.0	90.4	1.1
Nakuru County	4	91.3	2.7	91.1	2.7
Nandi County	5	94.0	0.0	89.0	0.3
Narok County	1	79.3	0.0	76.2	3.2
Nyamira County	6	87.0	1.5	74.8	2.7
Nyandarua County	2	95.6	0.7	95.4	1.4
Nyeri County	4	93.5	1.0	93.5	1.0
Siaya County	10	85.1	3.2	84.0	4.5
Taita Taveta County	1	100.0	0.0	100.0	0.0
Tharaka Nithi County	4	96.3	0.4	94.3	0.4
Trans-Nzoia County	1	82.4	5.3	82.3	5.3
Turkana County	1	96.9	1.6	96.8	1.6
Uasin Gishu County	4	95.2	0.7	95.0	0.7
Vihiga County	7	89.5	1.6	84.0	2.1
West Pokot County	1	91.3	2.6	90.8	2.6

Table 3: Power availability and interruption data, as reported by devices in Kenya during the study period, including the effect of voltage stabilization.

A similar map for Nigeria is shown in Figure 27, with the underlying data in Table 4. From these data we see that the average availability of usable voltage, as reported by devices during the study period, varied from 5.9% to 59% among different states. While there are multiple clusters of states with devices reporting similar power availabilities, additional data would be required to make conclusions about broad geographic trends beyond the states evaluated.

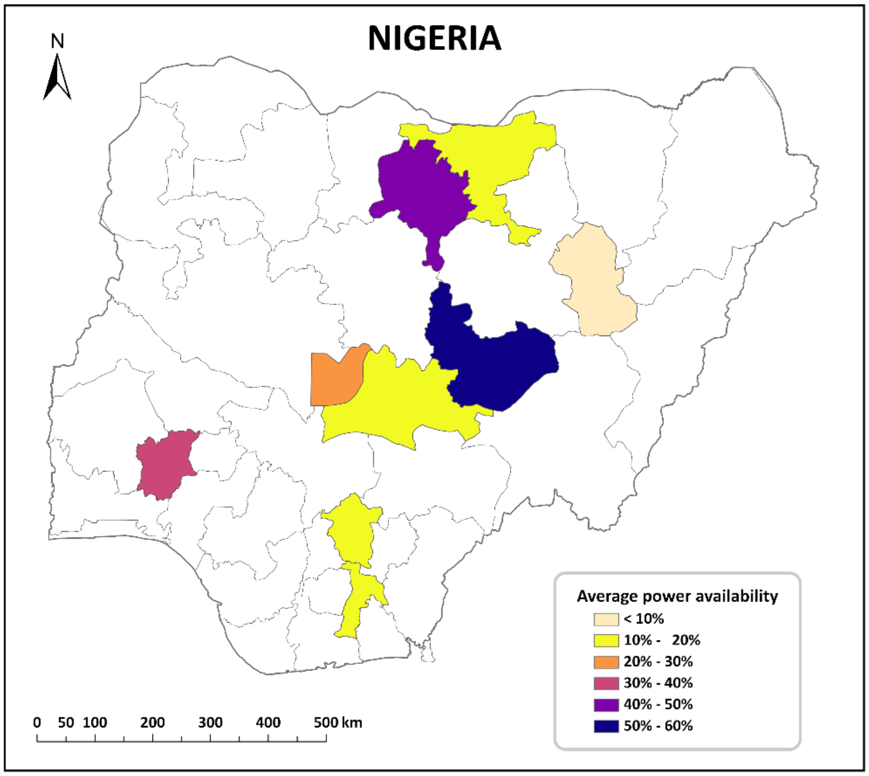


Figure 27: Average availability of usable voltage by state, as reported by devices in Nigeria during the study period (not measured in states with no color coding).

The impact of voltage stabilization on average power availability for each state in Nigeria can be seen in Table 4. In this case we see considerable variability between states—for example, in Enugu State voltage stabilization increased the availability from 14.9% to 20.8%, while in Gombe the availability increased from 5.9% to 22.0%. This demonstrates that voltage stabilization can make a substantial, but variable, improvement in power availability depending on the state.

State / Region	Number of Devices	Usable with Stabilization (110 V - 278 V)		Usable Range (207 V - 253 V)	
		Average Power Availability %	Average Interruptions > 48 hours per device year	Average Power Availability %	Average Interruptions > 48 hours per device year
Abia State	8	23.6	18.6	12.9	24.4
Enugu State	10	20.8	29.5	14.9	33.2
FCT Abuja	10	43.7	12.9	21.5	20.0
Gombe State	10	22.0	22.1	5.9	26.8
Jigawa State	9	34.3	17.7	15.4	51.8
Kano State	16	50.4	5.1	40.1	8.6
Nasarawa State	10	39.0	22.6	19.4	32.4
Osun State	10	51.4	7.9	39.2	10.6
Plateau State	10	72.4	2.2	59.4	3.2

Table 4: Power availability and interruption data, as reported by devices in Nigeria during the study period, including the effect of voltage stabilization.

Multi-day interruptions

When we examine the geographic distribution of reported multi-day interruptions in Kenya, we find that many were reported by devices in western and central counties participating in the study, specifically outside the major metropolitan areas of Nairobi and Kisumu. The average number of reported multi-day interruptions (48 hours or longer) per county is shown in Figure 28. The underlying data can be seen in Table 3. The data are normalized per device per year (shortened to “per device-year”) to account for the differing numbers of devices and durations of measured data for each device. In other words, during the study period, each device in Kakamega County (20 total) could be expected to report two interruptions longer than 48 hours during each year.

We can see the effect of voltage stabilization on the incidence of interruptions in Kenya, if we consider “effective” interruptions to be periods when the voltage is outside the usable range as distinct from our usual definition of an interruption as a period when the voltage is not stabilizable. The rate of expected interruptions drops only slightly in most counties when stabilization is added. This demonstrates that the bulk of reported interruptions across all counties were due to significant voltage drops or blackouts, rather than undervoltage that can be stabilized. In all measured counties, incorporating electrical or thermal energy storage (e.g., holdover time) may be a more effective method of increasing device performance rather than solely incorporating voltage stabilization.

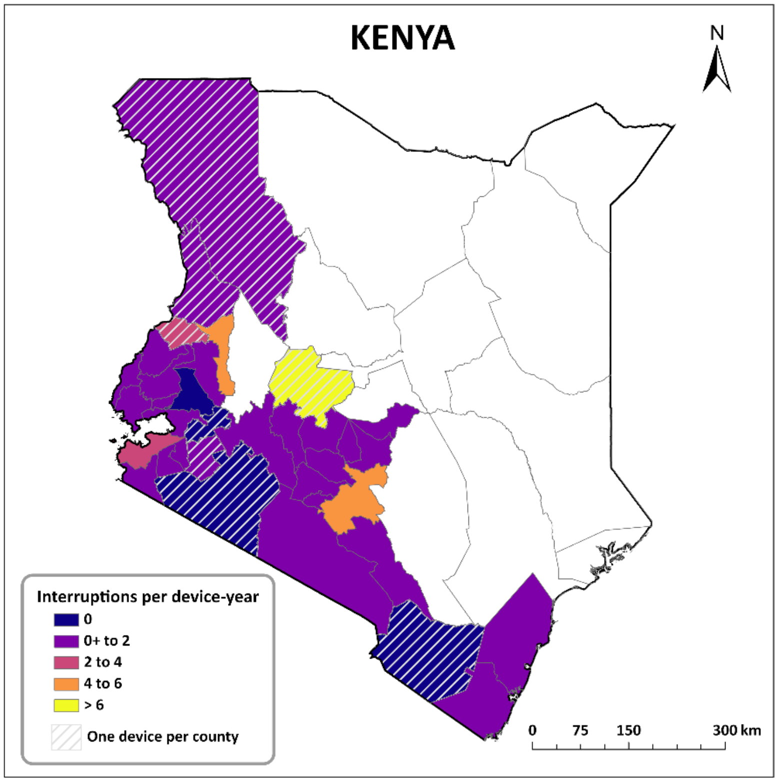


Figure 28: Average interruptions 48 hours or longer per device-year by county, as reported by devices in Kenya during the study period. Cross hatching denotes counties with a single device.

A similar map for Nigeria (Figure 29) shows variability in the interruptions from state to state. For example, devices operating in Plateau State typically reported 2.2 multi-day interruptions per year, while devices operating in Nasarawa State reported on average 22.6 interruptions 48 hours or longer per year. As with power availability, there is some clustering but limited broad geographic trends (e.g., east vs. west interruption behavior), so it is difficult to infer what interruption behavior there might be in states where measurements were not collected. In Table 4 we can see the impact of voltage stabilization on interruptions, where there is again a significant but variable reduction in the number of multi-day interruptions expected per year.

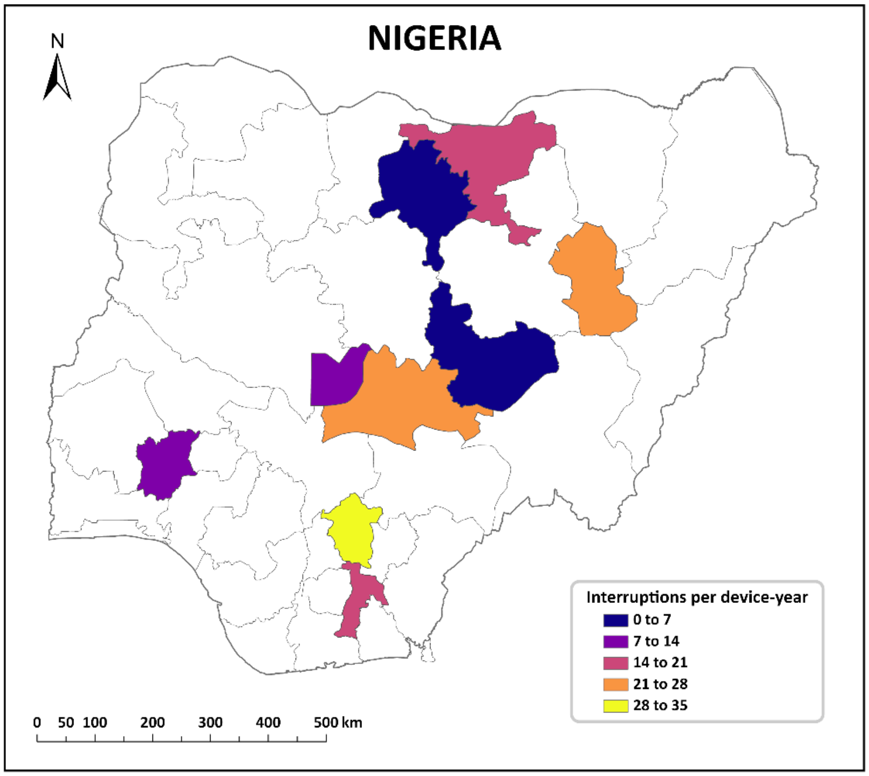


Figure 29: Average interruptions 48 hours or longer per device-year by region, as reported by devices in Nigeria during the study period.

In both Kenya and Nigeria there is a correlation between power availability and prevalence of multi-day interruptions. This can be seen in both Table 3 and Table 4, where counties/states with lower average power availability also tend to experience a larger number of multi-day interruptions.

6 Conclusions

We conducted a nearly 18-month longitudinal analysis of mains electricity availability and quality measured by devices in health facilities in two LMICs, Kenya and Nigeria. Power data were measured and telemetered by WHO–prequalified vaccine refrigerators (heretofore referred to as devices) operating in 210 facilities in Kenya and 93 facilities in Nigeria. Although the reported power profiles in these countries were quite different from one another, data collected in both countries during the study period indicated power conditions that could compromise the reliable operation of mains-powered priority medical devices and equipment. Our major conclusions are:

Reported voltages deviated significantly from nominal, so voltage stabilization can improve equipment reliability and lifespan.

In Nigeria, 76 of 93 devices (82%) reported usable voltage less than 50% of the time. This is the equivalent of 15 days or more a month of unusable voltage. Providing WHO-prequalified PQS extended range voltage stabilization reduces the number to 66 devices (71%) with usable voltage less than 50% of the time. Moreover, it shifts many of the devices with 0% to 20% availability closer to 50% availability. Although reported line voltage in Kenya during the study period fell within the usable range for most of the time in the aggregate, 6 of 210 devices (3%) reported usable voltage less than 50% of the time. Providing WHO-prequalified PQS extended range voltage stabilization would improve this statistic to only 4 devices (2%) with usable voltage less than 50% of the time. This indicates that voltage stabilization would benefit individual health facilities where high power availability levels, reliable operation, and long lifespans are required for medical equipment, even if the country-averaged power availability statistic may appear to be adequate.

Interruptions were common, and many health facilities experienced them.

While most reported service interruptions during the study period were short, devices in Kenya and Nigeria reported a significant rate of multi-day interruptions at the health facility level. Sixty-eight percent (68%) of facilities in Kenya and 92% of facilities in Nigeria experienced interruptions in excess of 48 continuous hours at some point during the study period. These data indicate that devices requiring continuous operation (e.g., vaccine refrigerators and freezers) should be designed for multi-day interruptions, even when intended for locations that are expected to have relatively reliable electrical grid service. Finally, as demonstrated in Figure 14, voltage returns following service interruptions can be ephemeral, indicating the importance of a start delay for medical devices and equipment susceptible to premature wear from excessive on/off cycles.

Extreme voltage and frequency conditions can pose a risk of permanently damaging medical equipment.

In both countries devices reported voltage conditions that can potentially permanently damage improperly protected equipment. Voltage sags and sustained undervoltage can damage medical devices and equipment through overheating of motors or other electronics. Devices also reported hours- or days-long periods of transient undervoltage, where the voltage varied as much as 60 V over periods as short as 10 seconds and as long as 10 minutes. Rapid voltage changes occurring as frequent as once every 10 seconds can be challenging to stabilize, thereby posing risks both to stabilizers and to the equipment they protect. Overvoltages can also pose a challenge, with 15 of the total 303 devices in both countries during the study period reporting overvoltage events in excess of 350 V, and 4 devices experiencing voltages in excess of 450 V. Although comparatively rare, it only takes a single event to disable equipment. Also, devices were not designed to measure or report very short overvoltages, such as those originating from lightning strikes or arcing in switches, which can also pose a threat to insufficiently protected equipment.

With regard to frequency variability, devices reported frequency outside of the 45 Hz to 55 Hz range in Kenya 0.1% of the time, with measured frequency mean of 50.1 Hz and standard deviation of 0.64 Hz during the study period.

In Nigeria, although the mean frequency was 50.0 Hz with standard deviation 1.9 Hz and frequencies outside the 45 Hz to 55 Hz range were reported 2.2% of the time in the aggregate, some devices in facilities experienced extended effective interruptions due to frequencies maintained outside the 45 Hz to 55 Hz range. These data demonstrate that, while rarely reported within our study, frequency excursions can happen and adequate frequency protection should be considered when designing devices and equipment for use in LMIC health facilities, particularly voltage stabilizers.

In both countries, devices reported variations in power availability from county to county and state to state. During our study period, devices in the southeastern part of Kenya had usable power more than 88% of the time, while those in the central and western counties experienced less availability, except for urban Kisumu and Nairobi and surrounding Counties. In Nigeria, however, patterns were more difficult to discern.

Priority medical devices and equipment that use grid power in LMIC health facilities need to be designed to handle the conditions described in this analysis, including but not limited to multi-day interruptions and extended under- and overvoltages. While Kenya and Nigeria are not fully representative of all LMICs, it is our hope that this analysis and its data supports the specification, engineering, and procurement of equipment that can perform reliably and over longer lifespans in challenging environments, leading to improvements in global access to quality health care.

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Appendix A: Additional Voltage Time Series

The following plots show more examples of voltage varying from the usable or stabilizable ranges over the course of the study.

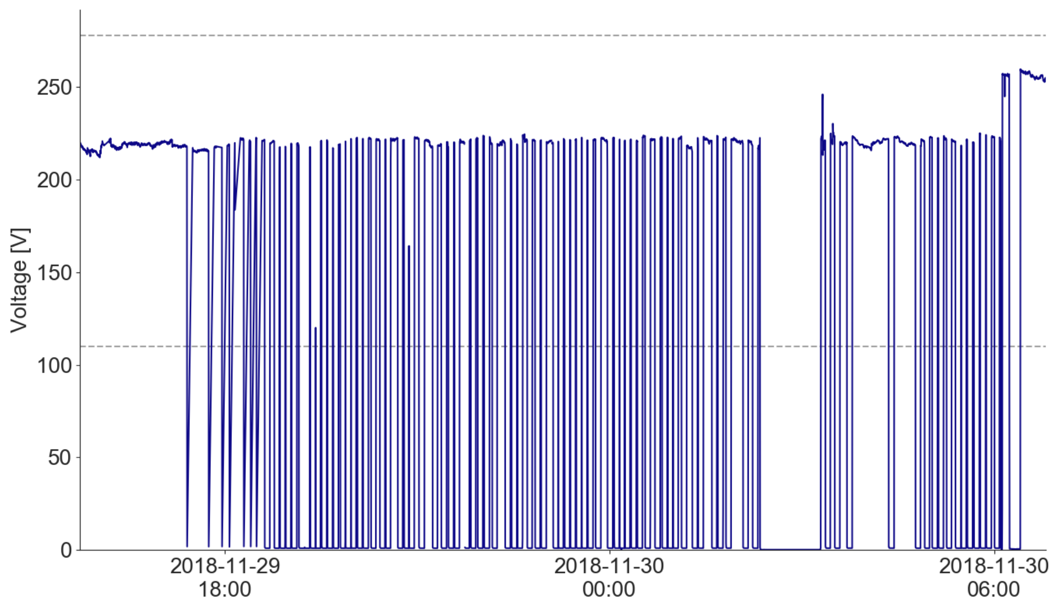

Figure 30: Multiple interruptions, device K-198.

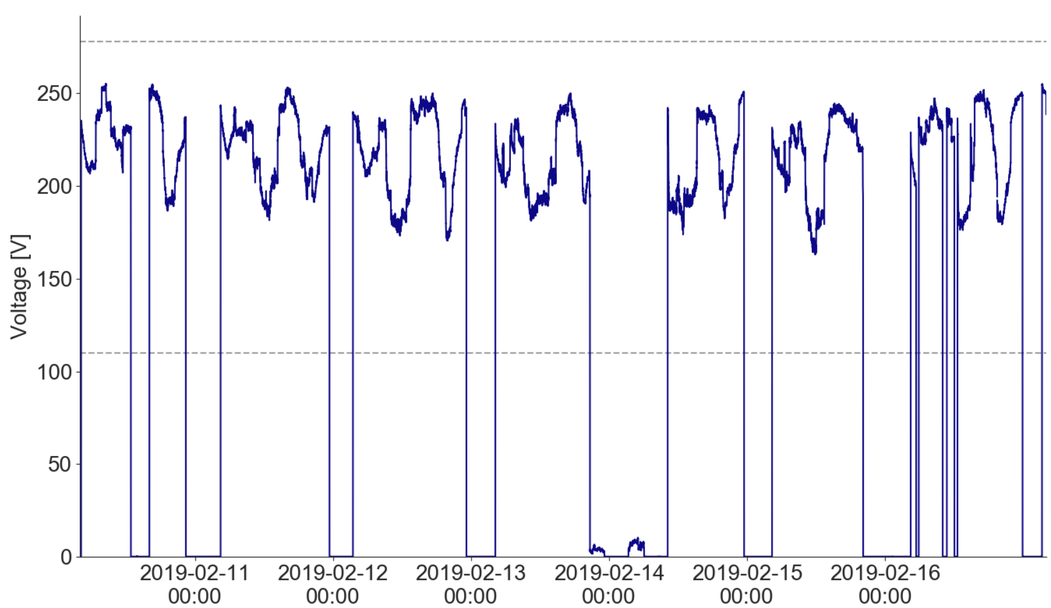

Figure 31: Daily variations and interruptions, device N-067.

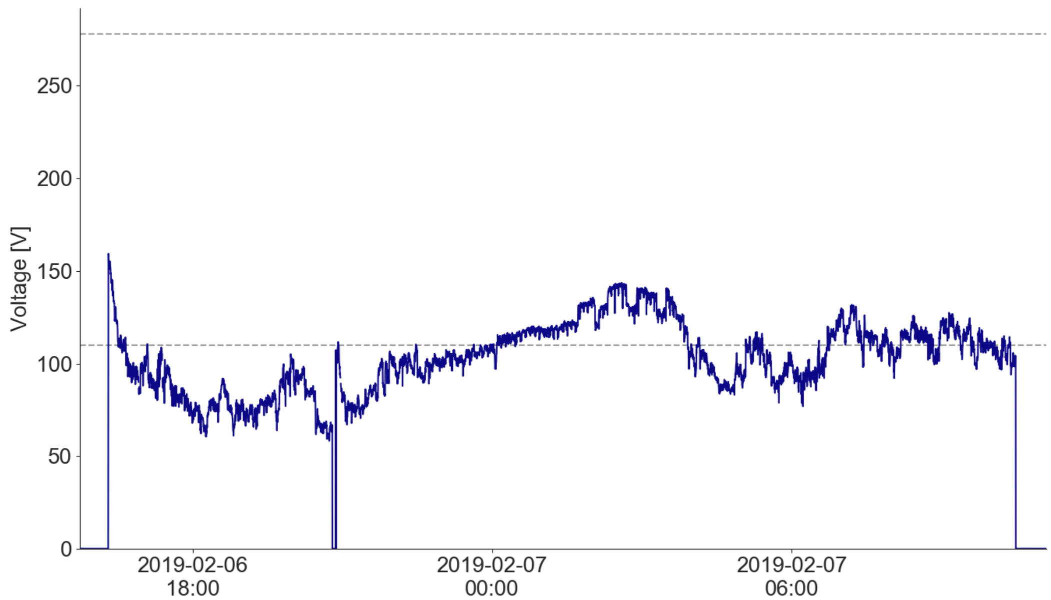

Figure 32: Voltage varying near the border between stabilizable and unusable over 12 hours, device N-044.

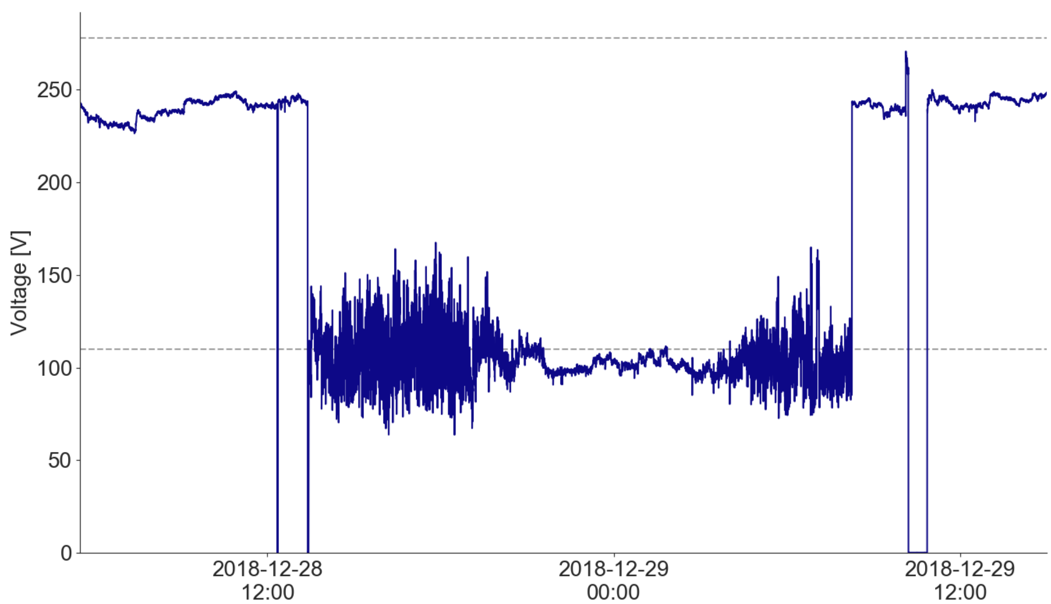

Figure 33: Voltage varying near the border between stabilizable and unusable over 19 hours, device K-001.

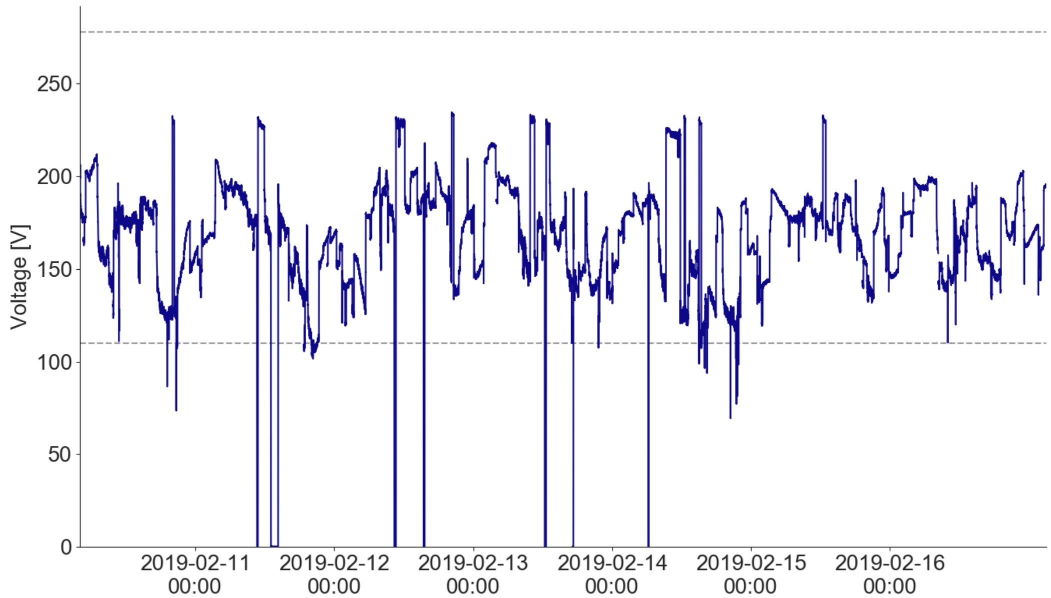

Figure 34: Variable voltage mostly in the stabilizable range over a week, device N-049.

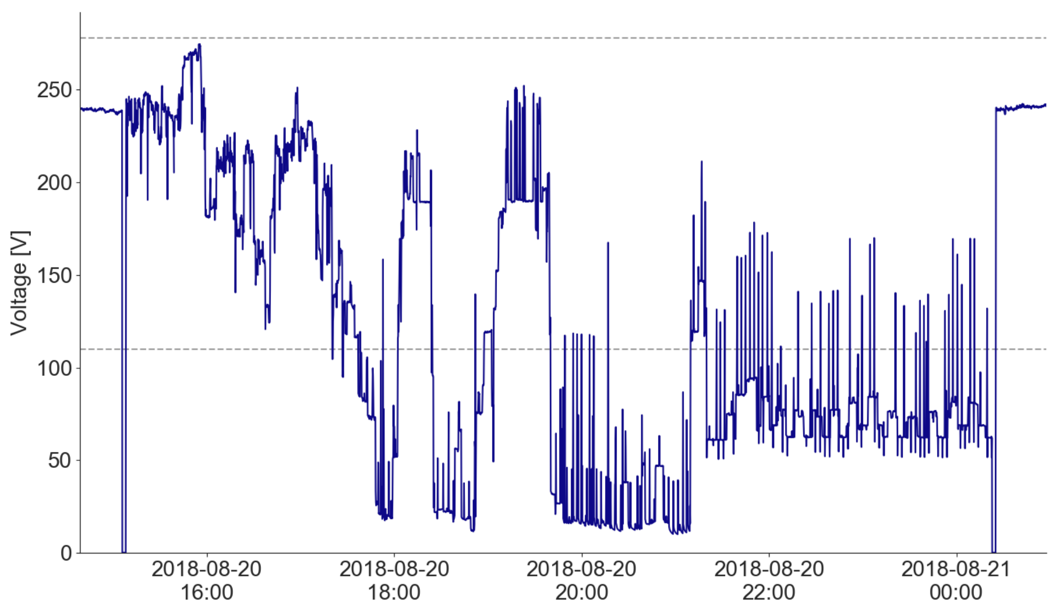

Figure 35: Variable voltage, device K-117.

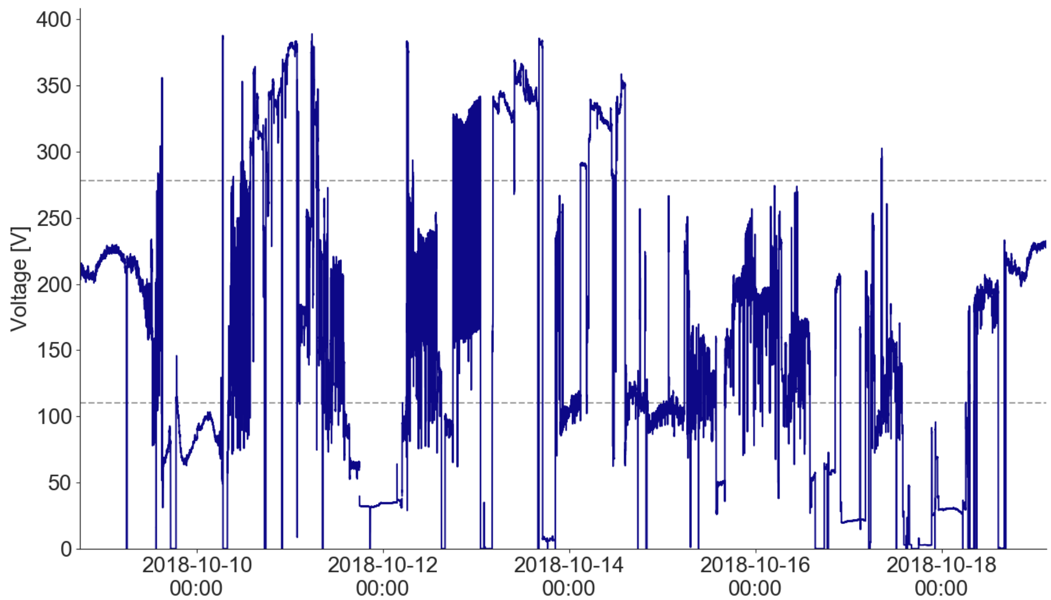

Figure 36: Variable voltage including overvoltage, device N-048.

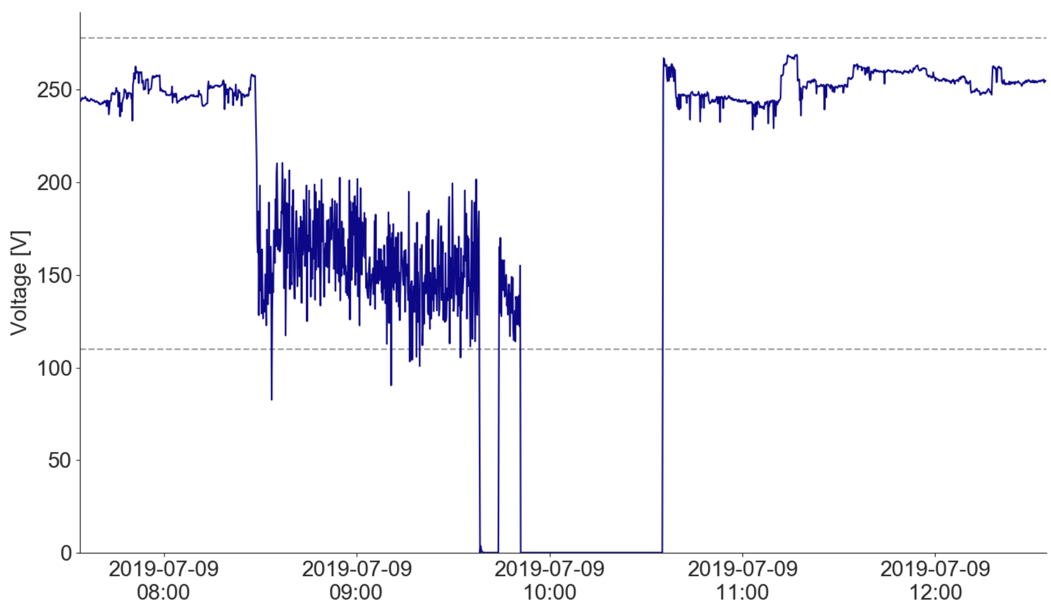

Figure 37: Variable voltage mostly within the stabilizable range, device K-154.

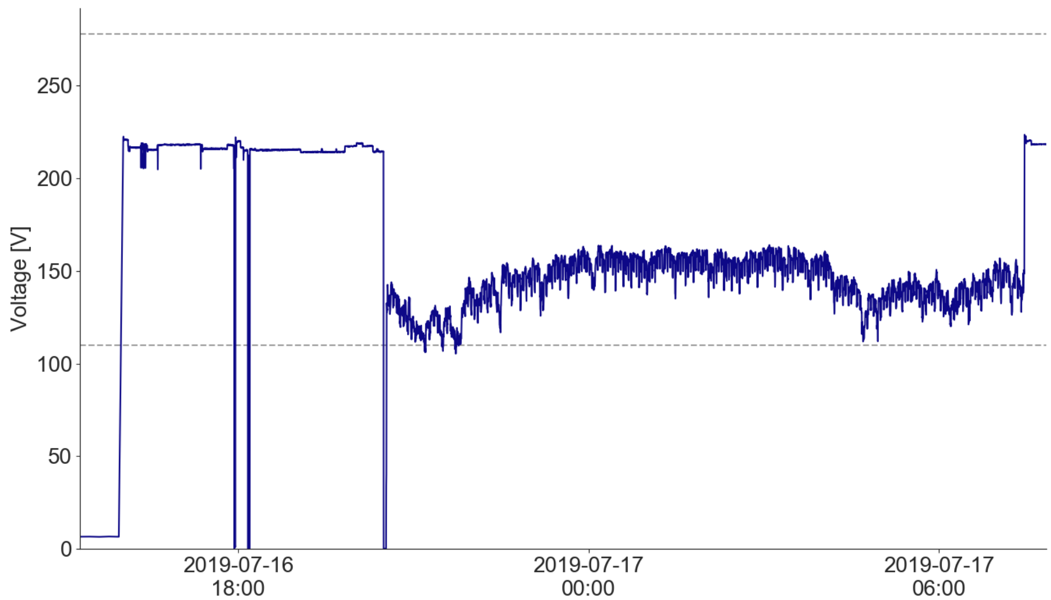

Figure 38: Variable mostly stabilizable undervoltage, then return to usable range, device N-001.

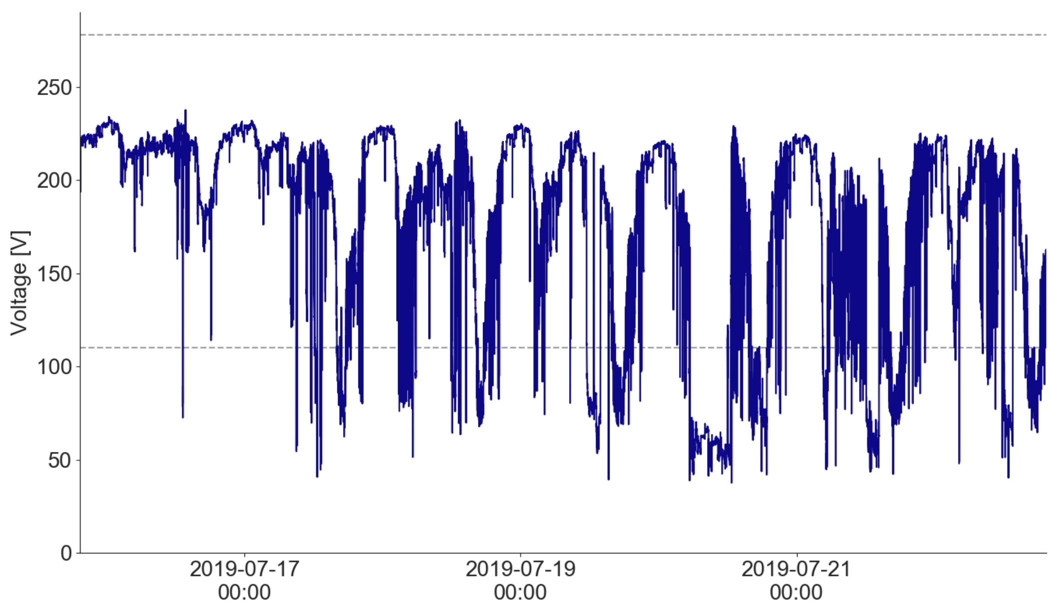

Figure 39: Variations with a pattern that has an approximate daily period, device K-036.

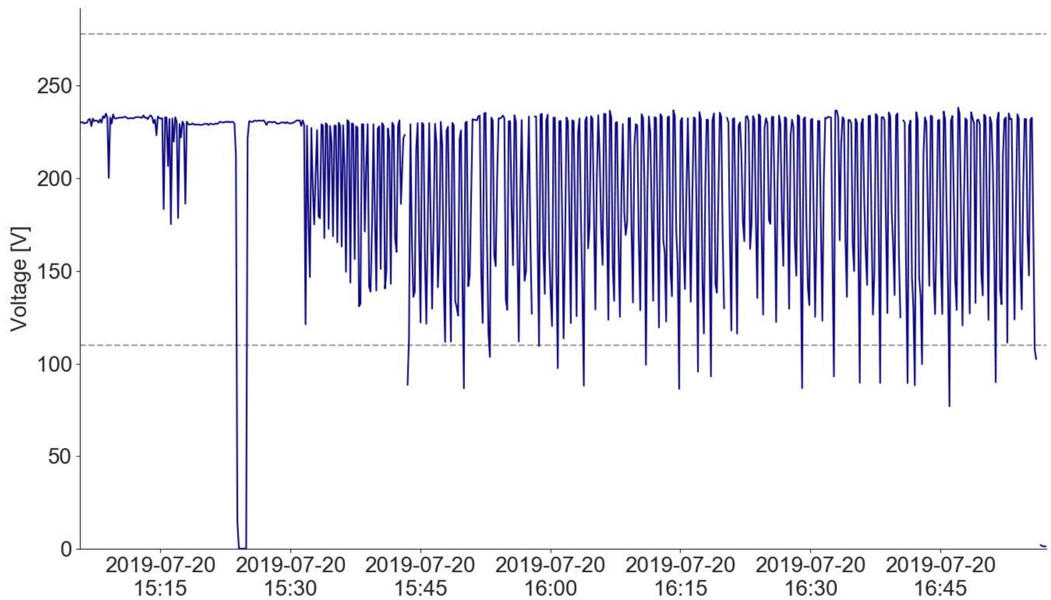

Figure 40: Rapid fluctuations, device N-054.

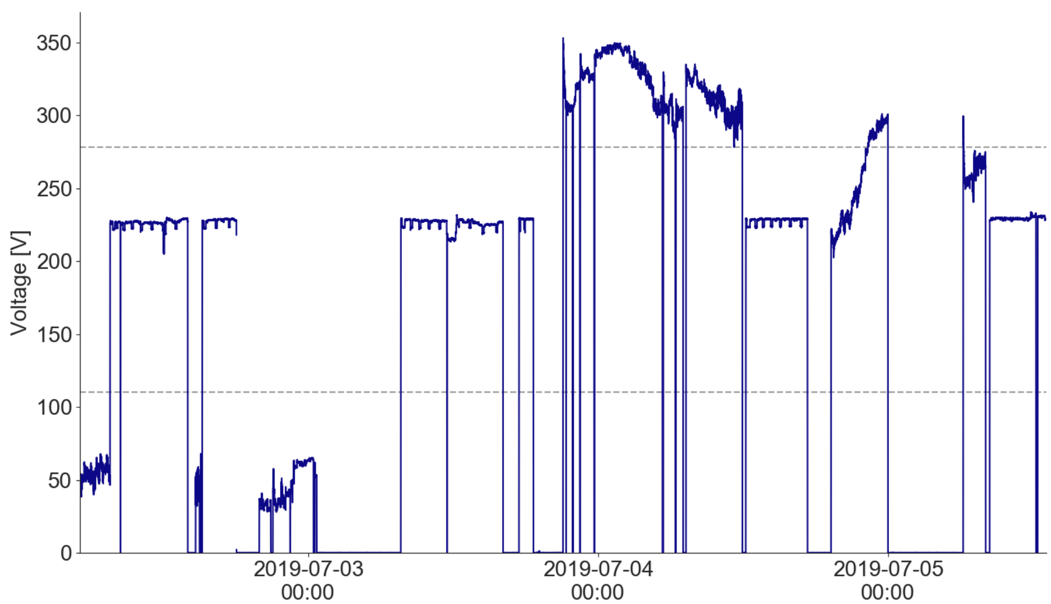

Figure 41: Usable voltage, overvoltage, undervoltage, and zero voltage over a 3-day period, device N-044.

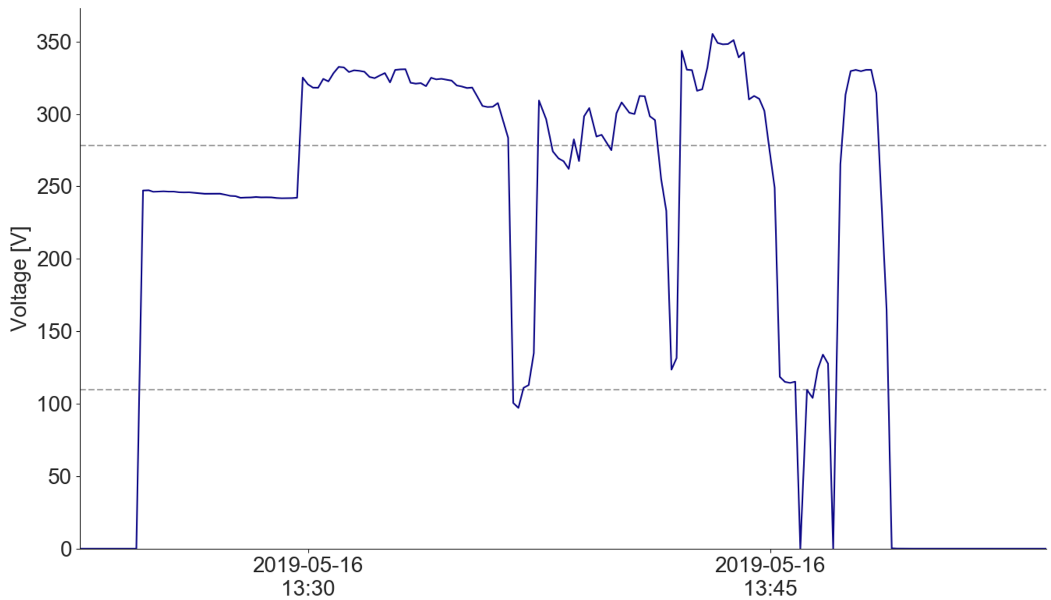

Figure 42: Undervoltage to overvoltage several times within a 15-minute span, device N-082.

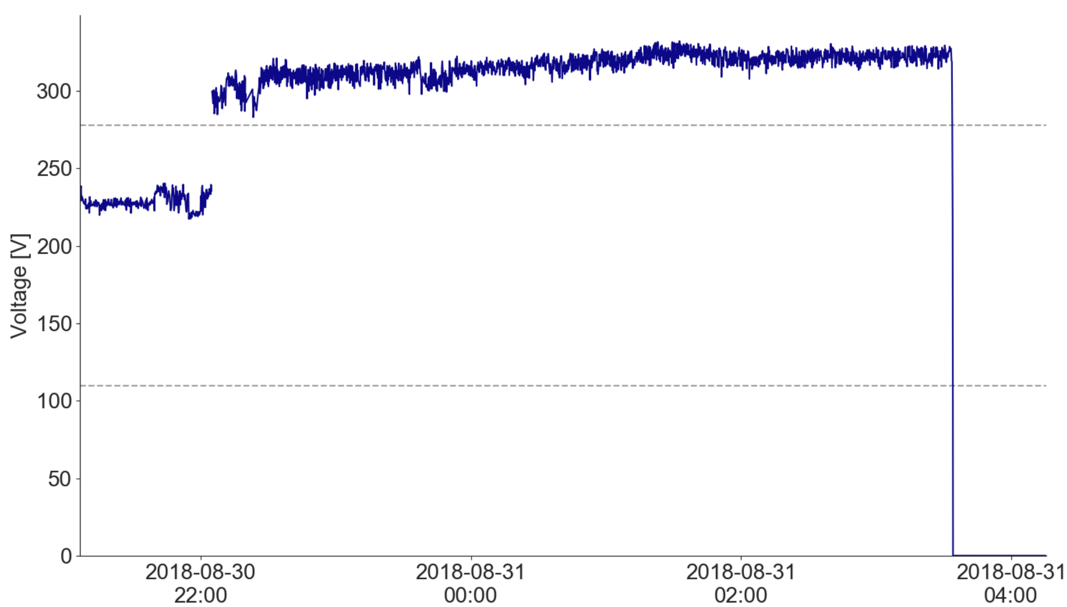

Figure 43: Overvoltage, device N-006.

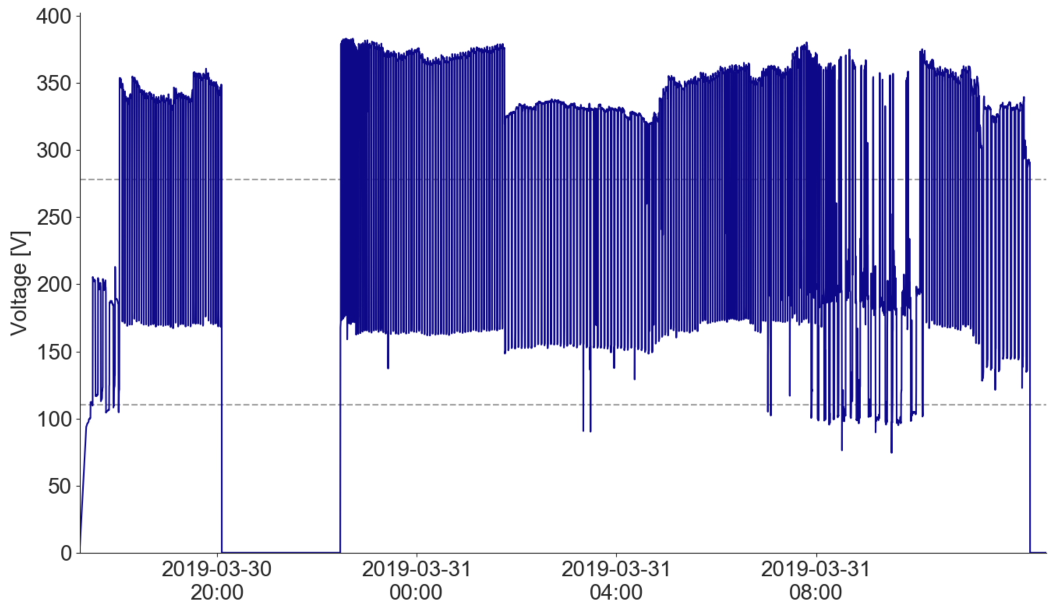

Figure 44: Square wave stepping between stabilizable undervoltage and unstabilizable overvoltage. The pattern is roughly periodic every 3-4 minutes, device N-070.

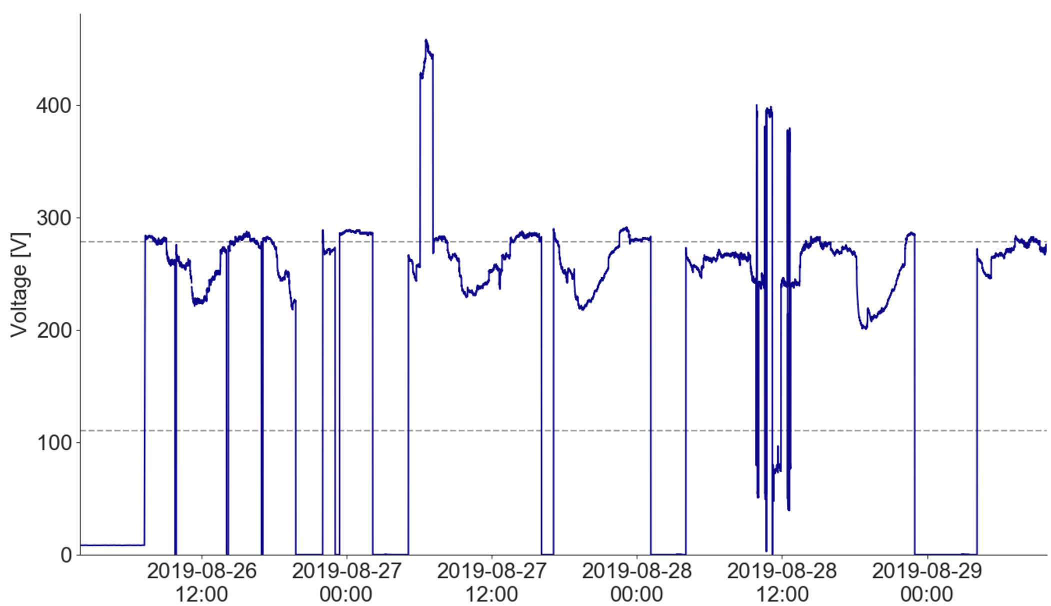

Figure 45: Fifty (50) minutes of overvoltage reaching 456 V, and another overvoltage the next day. This is device N-067, the same one in Figure 31, and shows a similar pattern of daily variation.

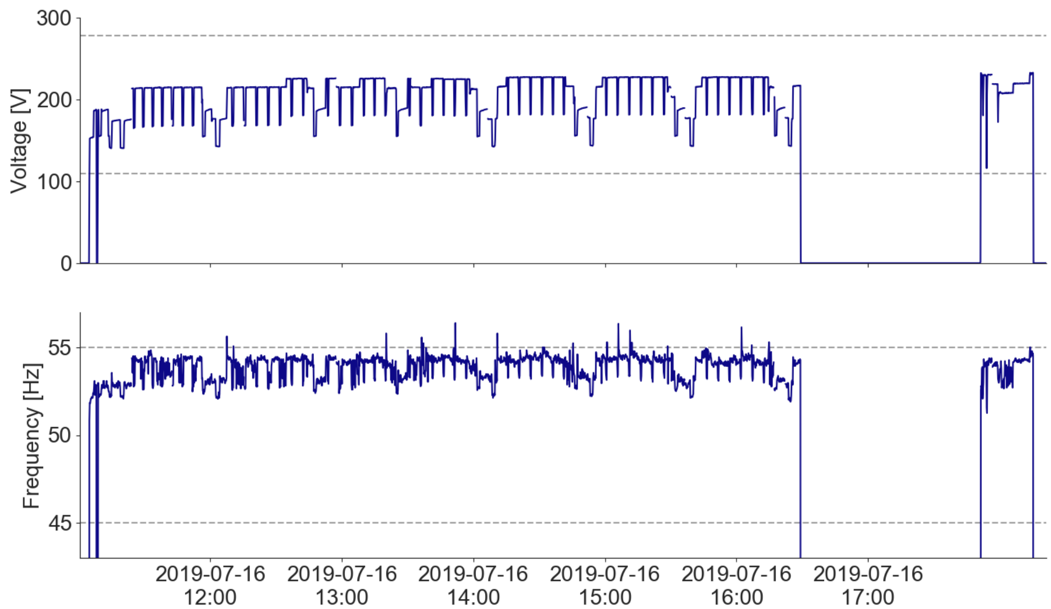

Figure 46: Voltage and frequency varying with load, device N-060.

Appendix B: Availability of Usable Voltage, All Devices

These plots show the percentage availability of usable voltage reported by each device during the study period. The red bars show how much stabilization would have improved power availability for that device. Devices are sorted by percent of time with usable voltage.

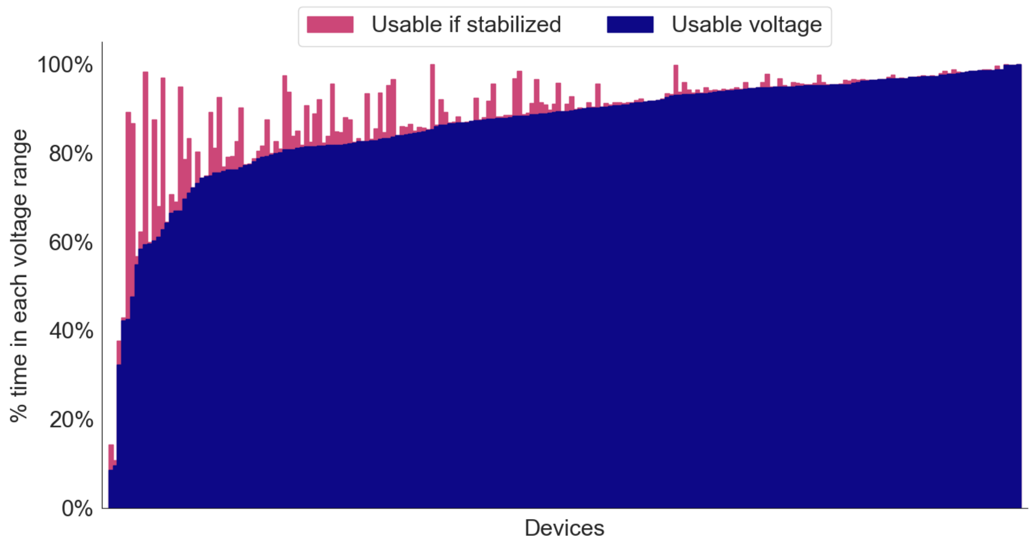

Figure 47: Percentage time in each voltage range for all 210 devices in Kenya.

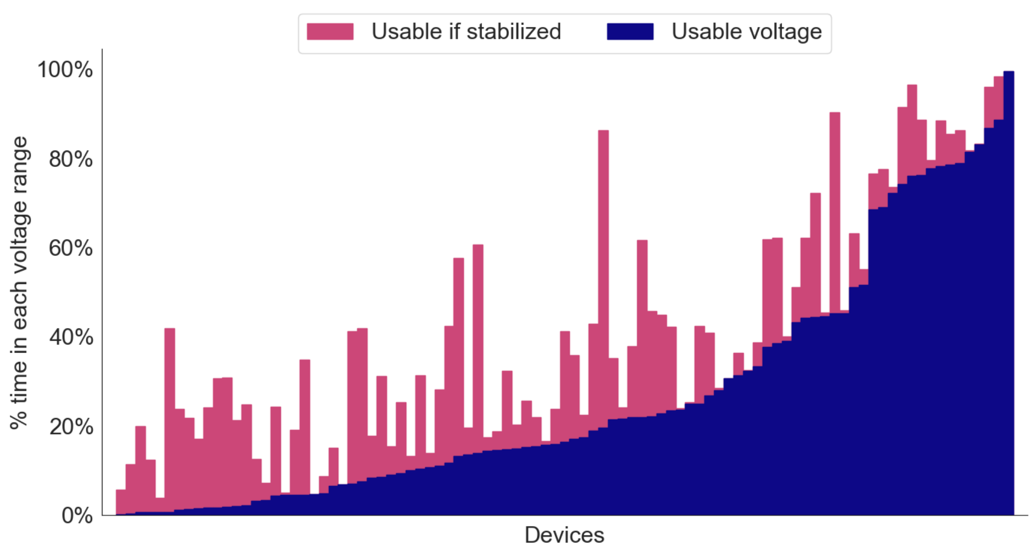

Figure 48: Percentage time in each voltage range for all 93 devices in Nigeria.