Power quality and modern energy for all

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"Modern energy for all," an internationally supported initiative to connect populations to electricity services, is expected to help reduce poverty-induced vulnerabilities. It has become a primary strategy for meeting sustainable development goals, especially in sub-Saharan Africa. However, when electricity is supplied by a capacity-constrained grid to a resource-constrained population, the service quality can vary both spatially and temporally. This research explores the quality of electricity services based on a case study of Unguja, Tanzania. Using 1) open-ended interviews, 2) detailed electricity-systems monitoring, and 3) household surveys, we show how voltage quality varies significantly, even within highly localized settings. Fluctuations result in dim lights at best and power outages and broken appliances at worst, denying many Unguja residents the expected benefits of access to modern energy. By combining an extensive understanding of the physical system together with interviews and surveys, this work presents a unique mapping of voltage quality in a system that is financially and physically constrained and highlights the consequences of poor-quality service for poor users.

power quality | electrification | SDG 7 | development | Zanzibar

Safe lighting, a working TV, and a charged cell phone have arguably become basic needs in today's world. Increasing access to electricity services, therefore, has become a primary strategy for meeting international development goals. Nongovernmental initiatives, as well as foreign aid and foreign direct investment efforts, are devoted to increasing electricity access to improve human conditions in poor communities (1). The most prominent expression of these efforts is Sustainable Development Goal 7 (SDG 7)—the United Nations' initiative to "ensure access to affordable, reliable, sustainable and modern energy for all" (ref. 1, p. 9). The implicit assumption that electricity services will promote better lives if provisions are adequate and equitable underpins SDG 7 as a key sustainable development goal.

In sub-Saharan Africa (SSA), with international donors and local governments investing in grid expansion, ∼190 million people gained access to electricity between 2000 and 2014 (2). Recent work has focused on SSA's renewable energy potential, attempting to displace carbon-intensive generation sources in an affordable manner (e.g., refs. 3 and 4). Expanding grid access, regardless of energy source, entails costly transmission and distribution infrastructure (5). These services and systems in SSA are routinely described as inadequate (6), unreliable (7), and disrupted (8). In this paper, we refer to such electrical systems as "constrained," because the distribution systems are capacity constrained and also serve financially constrained populations. Power outages, brown outages, and voltage fluctuations are commonplace in these systems, which continue to expand in Africa and Asia. In contrast, in high-income countries, customers typically face fewer than 5 h of service interruption per year (9, 10). For the majority of households across the United States and Western Europe, power outages and voltage variability are not a concern; the grid supplies near-constant and unvarying electricity.

This research provides an empirical description of the nature of electricity access under a constrained grid in the SSA community of Unguja, Tanzania. We focus on electricity quality, in particular on voltage along the distribution system. Electricity access scholarship has moved beyond discussing connections (11, 12) and has begun to incorporate dimensions of customer experience, such as reliability and voltage quality [e.g., the multitier framework of the World Bank and the International Energy Agency (11)]. However, little existing work illuminates the extent to which power quality shapes de facto access in SSA households; most research to date on power quality focuses on businesses and industry (13, 14). Aklin et al. (12), one of the few studies to engage with power quality at the household level, relies only on household perceptions to capture incidences of low voltage. Lee et al. (ref. 15, p. 6) concludes unequivocally that "we currently have almost no data on even the most basic patterns of outages in developing countries."

We measure household-level power quality in Unguja by monitoring voltage fluctuations on the local grid. We highlight its implications for adequacy and equity within the service area. Our work reveals the everyday unreliability of electricity in, and the consequences of unreliable services for, income-constrained households. As capacity-constrained grid systems such as the one in Unguja expand, this research speaks to how energy and development scholars characterize and analyze the quest for "modern energy for all."

The Unguja grid reaches more than 50% of households (16). Financed in part by the Norwegian Development Agency and managed by the Zanzibar Electricity Corporation (ZECO), grid services in Unguja are described as unreliable (17). ZECO serves a population whose (self-reported) monthly income in 2013

Significance

This research provides a detailed mapping of voltage quality in a sub-Saharan African (SSA) community and connects power systems data to household surveys and interviews for a comprehensive understanding of life under an unreliable grid. Reliability within the context of "modern energy for all" in SSA has traditionally focused on power outages rather than voltage quality and on businesses rather than households. Our research expands on energy access scholarship and reliability concerns in SSA by offering an illustrative case study of access in Unguja, Tanzania. As electricity access expands in financially constrained communities, creating capacity-constrained connections, our Unguja study offers a crucial look at what that access means for SSA communities.

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ranged from 50 United States dollars (USD) to 200 USD (18). However, residents pay roughly $.13/kWh, a rate comparable to several high-income countries, rendering many uses of electricity a luxury.

Unguja is not exceptional. Reports across SSA reveal an electricity landscape characterized by poor quality and costly service (2, 19). Poor voltage quality is characterized by drops, sags, fluctuations, and spikes. Electric utilities set an allowable range for voltage fluctuations, commonly $\pm5\%$ of the nominal voltage ($\pm5\%$ of 120 V), as in the United States, or $\pm10\%$ ($\pm10\%$ of 220 V), as in Unguja. In high-income countries, distribution feeders have instruments such as capacitor banks to maintain the desired voltage along the transmission lines. Limiting voltage fluctuations is important because, although common household appliances can function with small deviations outside of the allowed range, they can be damaged by larger deviations (20). For example, motors found in fridges, blenders, or electric pumps can overheat with voltage fluctuations, thus decreasing their lifespan (21). Similarly, the incandescent light bulbs commonly used in SSA, and also in Unguja, break faster with voltage fluctuations. Compact fluorescent lamp (CFL) and LED light bulbs are supposed to function the same regardless of voltage, but the light intensity for CFLs can vary with voltage (22), and the cheaply made versions that many financially constrained people buy are susceptible to breakage under large voltage fluctuations (23).

Our research offers a unique mapping of voltage quality in Unguja and provides insights into the consequences of poor quality electricity services on household welfare. This study measures and documents the lived experience of the near-daily and unpredictable voltage fluctuations in the region. Our mixed-methods approach included 62 open-ended interviews, 151 household surveys, and electric power systems monitoring over the course of 2 y—using monitoring devices designed by Power Standards Laboratory (24) and devices that our team designed and built specifically for the study. In the following sections we lay out our results and discuss the implications of our research for the pursuit of modern energy for all.

Results

Power-Quality Variation in Unguja. Fig. 1 shows the study locations, marked as small circles and squares, with the lines representing the centralized grid. Our interviews with ZECO customers suggested that temporal and spatial voltage differences characterized electricity access on the local distribution system. For instance, "Electricity is variable - it cuts out, then comes back. This can be like four times [in a day]." Others agreed that "electricity goes up and down [without warning]" (*Materials and Methods*). A refrigerator salesman explained spatial variation, saying that, "if you are far away from the transformer, then the electricity the household gets is less stable than if you were closer to the transformer."

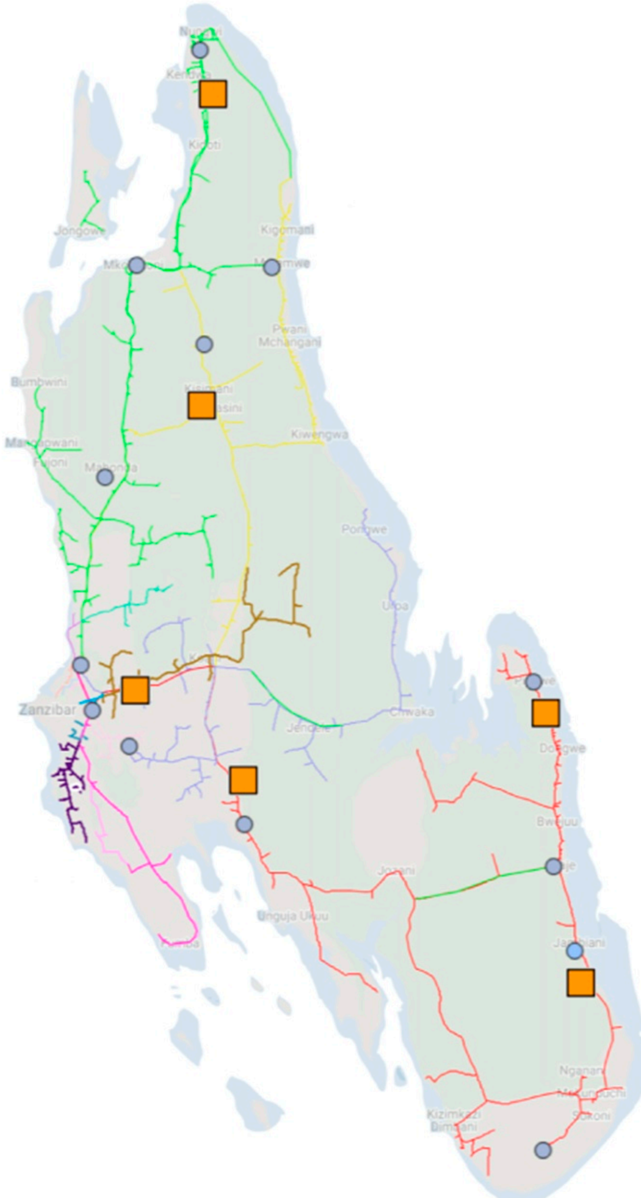

Fig. 1. Map of Unguja with approximate grid schematic. Circles indicate regions where interviews took place, while squares indicate regions where initial voltage measurements took place (25).

Voltage monitoring measurements across the island (Fig. 1) revealed localized voltage fluctuations as well as regional disparities, with some houses experiencing levels well below the island's nominal voltage of 220 V. Fig. 2 shows voltage profiles for 2 households connected to the same distribution feeder, with one transformer. The household toward the end of the feeder (farther from the transformer) experienced lower average voltage and significantly worse fluctuations, dropping as low as 155 V (30% below nominal). In such an environment, customer loads and electrical equipment are not expected to operate reliably or as designed (26).

For a more granular view, we instrumented households in 2 sites (A and B) with low-cost voltage sensors (Fig. 3). The sites had similar socioeconomic status but were located on distinct parts of Unguja's grid; results from 2 different feeders are more robust than those from a single feeder (*SI Appendix*). We collected voltage data between December 2016 and June 2017. Each sensor is represented by a letter in Fig. 3, with sensor a closest to the transformer. Figs. 4 and 5 show the voltage drops across the sensors for each site, with the *y* axis showing per unit (PU) voltage (voltage measured divided by nominal voltage [220 V]). The shaded region indicates $\pm10\%$ of nominal voltage (1.1 to 0.9 in PU). Although voltage profiles at each sensor varied from week to week, there is a general dropping trend with distance from the transformer. However, voltage does not drop monotonically down the feeder; the time of day clearly matters (Fig. 2). Furthermore, in site B, sensor e captured mean and maximum voltages higher than at sensors c and d (Fig. 5).

These voltage fluctuations are outside of the range of acceptability by any standard we are aware of. However, as low voltages affect end-use devices differently, these measurements alone are insufficient to understand the effect that constrained grids have on customers. For example, one interviewee said that his voltage

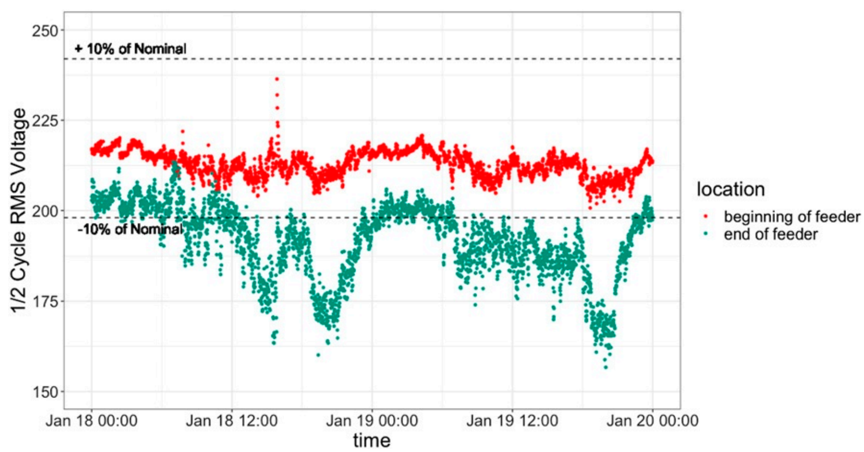

Fig. 2. Voltage measurements at 2 households on the same distribution feeder taken in January, 2017. The dashed lines indicate ±10% of the nominal voltage (220 V).

always dropped when his neighbor used his welders, while others did not recall any voltage variability. To explore these effects further we conducted detailed household surveys on customer experiences and perceptions.

How Power Quality Variation Is Experienced. Surveys from 151 households revealed an array of damaged electrical appliances, from fridges to light bulbs, across all socioeconomic strata. Pooled results from sites A and B revealed similar losses of appliances. Thirty-eight households identified appliances in their home that were not working. Five of these households had multiple broken appliances, such as fluorescent lights, fans, radios, televisions, electric cookers, refrigerators, and irons. One interviewee reported that his fridge had broken after a power surge. Another agreed, noting that after a power outage, he came home to a broken television and fridge. Asked about the lifespan of light bulbs, one participant replied, "usually they last about three months. Electricity goes up and down, up and down… so they never last [as advertised]." Many interviewees echoed this observation. An electric appliance shopkeeper noted that when customers purchased a fridge without a voltage stabilizer, they often returned to the store, fridge broken. Even low-end fridge

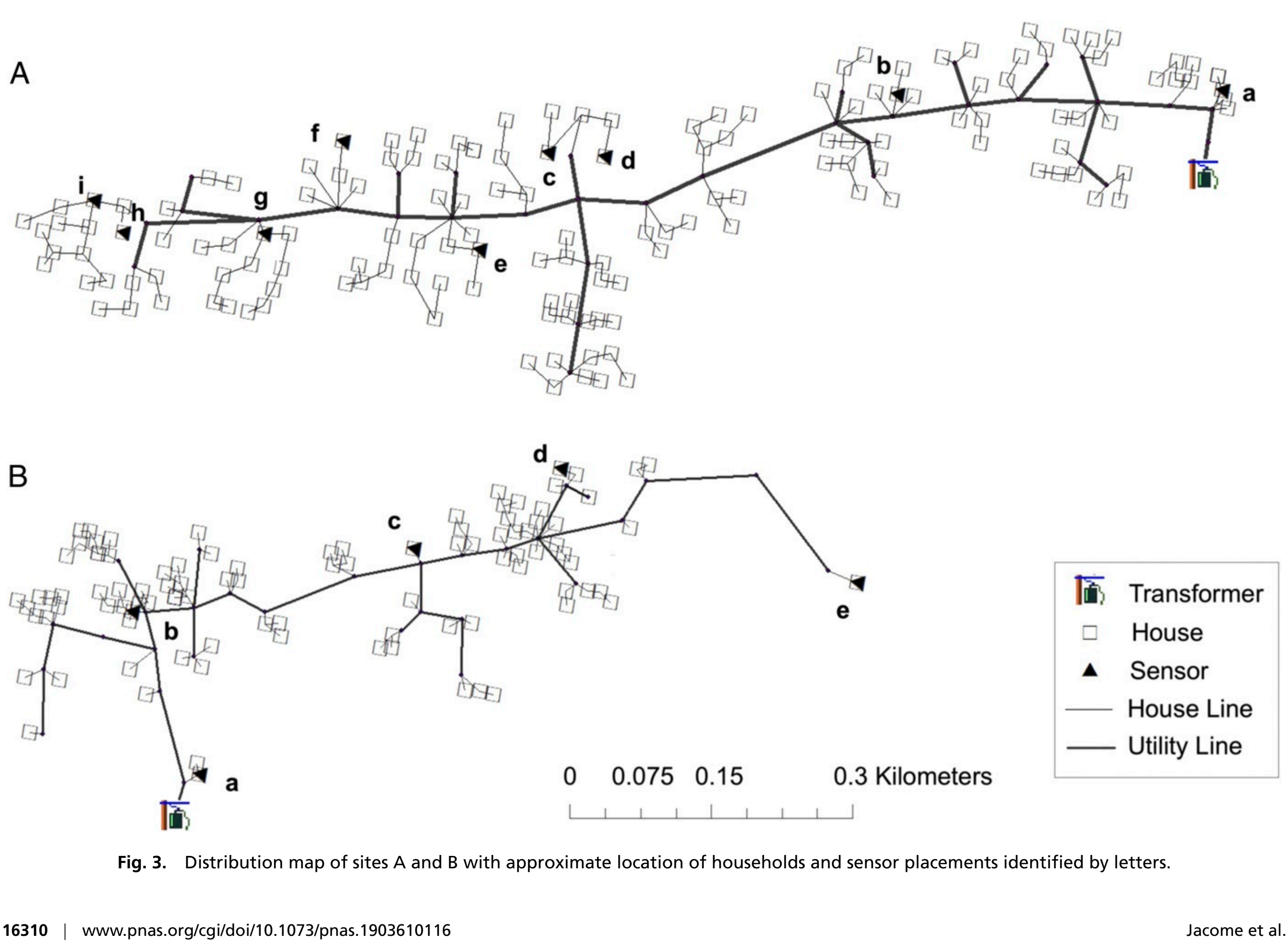

Fig. 3. Distribution map of sites A and B with approximate location of households and sensor placements identified by letters.

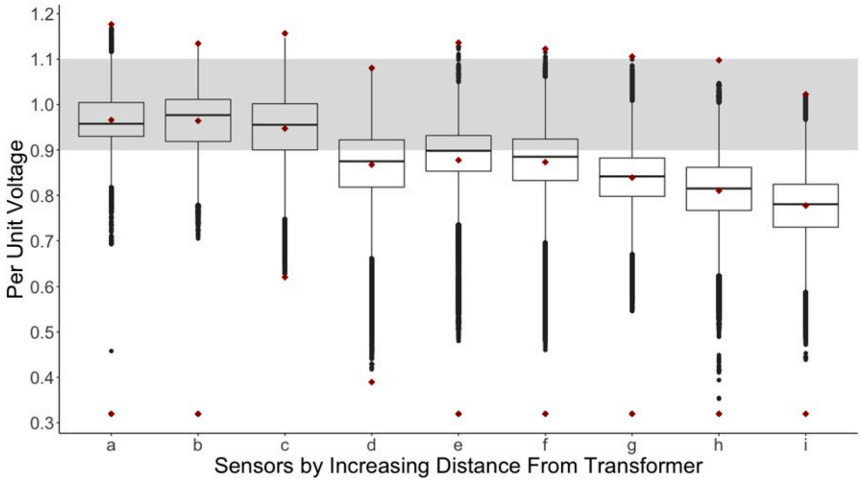

Fig. 4. Per unit voltage (base 220 V) measured at corresponding sensor location in site A. Black circles represent measured observations, averaged over 1 min. Red diamonds represent maximum, mean, and minimum voltage, without outlier observations and 0 measurements. Shaded region indicates ±10% of nominal voltage.

stabilizers on the island cost 20 USD, or up to 40% of the 2013 monthly income. Another participant explained, however, that a voltage stabilizer was not a guarantee against material loss: "I was using a stabilizer. There was a short in the stabilizer so the current went straight through. I lost everything."

We cannot establish causality between poor power quality and the damage to these respondents' appliances; appliances break for many reasons other than voltage fluctuations. But our voltage measurements revealed periods in which voltage was well below the standard of 10% of nominal (27), which can, and does, lead to damaged appliances (20, 21, 28).

Respondents were asked whether they recalled any voltage-related problems in the past month. Reported voltage-related problems included everyday inconveniences such as dimming lights to the point that it was difficult to see, fans growing softer and "weaker," insufficient power for large appliances, and sudden voltage spikes that damaged appliances. Households were also asked to identify the 3 most severe problems associated with their electricity connection; the menu of response choices included voltage problems, billing, maintenance, utility problems, and several others (details in *SI Appendix*). We assigned a PU voltage to each survey response based on the mean PU voltage of the sensor closest to the respondent's household (see Figs. 4 and 5 and *SI Appendix* for further details). Fig. 6 shows responses, pooled for both sites, to the 2 questions based on their given PU voltage. While we found no clear pattern associated with experiences of voltage-related trouble in general (Fig. 6, *Left*), we found a positive trend between households' perceptions of voltage as a top problem and power quality (Fig. 6, *Right*). Specifically, for those that identified voltage fluctuations as a top concern, our measurements indeed corroborated their low power quality.

The appliances people owned also correlated with their perceptions of voltage quality. Those who owned only low-tier appliances (e.g., lights, televisions, or irons), which are common and less sensitive to voltage fluctuations, tended to raise fewer concerns about voltage than those who owned top-tier appliances such as fridges, freezers, or blenders. Fig. 7 shows that 8 of 52 (15%) participants who owned only low-tier appliances considered voltage-related problems a top concern, compared with 44 of 99 (44%) with top-tier appliances.

Discussion. This study provides household-level insights into the nature of electricity access in constrained systems, using Unguja, Tanzania, as an illustrative case. We found that the quality of electricity varied significantly for households connected to these grids. We captured extreme voltage fluctuations during certain hours, showing that, in these capacity-constrained conditions, when and how others on the same distribution line consume matter greatly for an individual household. Without boosters and voltage regulators, which utilities often do not provide, and without in-home ways to mitigate voltage drops, which low-income communities cannot afford, households farther down the feeder experienced worse voltage fluctuations than those near the transformer. Although some drops and fluctuations in voltage occur in all systems, the drastic voltage fluctuations across both sample sites indicate pervasive inconveniences and the risk of costly damages, undermining the promise of both adequacy and equity that universal connectivity is supposed to promote.

Our voltage measurements and household surveys show that having an electricity connection (i.e., access) is not at all the same as having a reliable or adequate electricity service (16). While rarely analyzed in the electricity and development literature, our work shows the many ways in which power quality and unreliability matter to low-income communities. The quality of electricity services shapes households' ability to use their "access." In Unguja, households reported lights that were too dim to be useful, larger appliances that could not be operated,

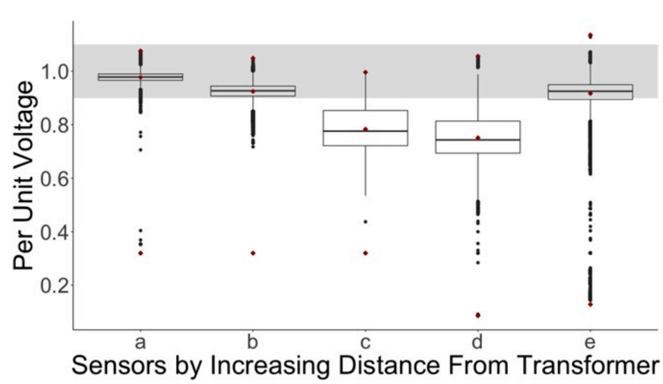

Fig. 5. Per unit voltage (base 220 V) measured at corresponding sensor location in site B. Black circles represent measured observations, averaged over 1 min. Red diamonds represent maximum, mean, and minimum voltage, without outlier observations and 0 measurements. Shaded region indicates ±10% of nominal voltage.

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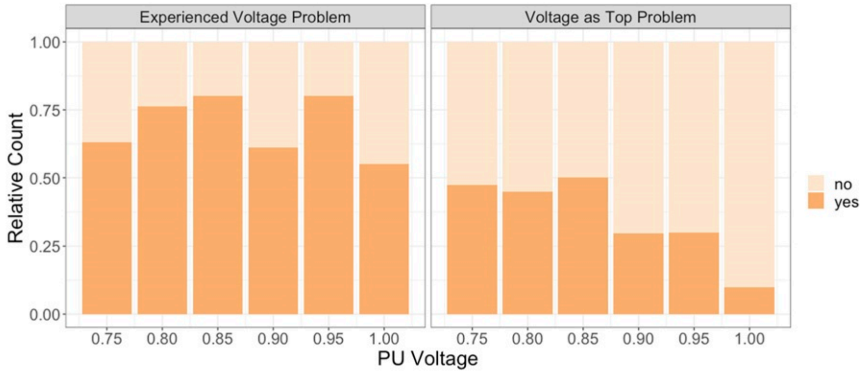

Fig. 6. Survey responses for both sites A and B vs. mean PU voltage associated with participating house (i.e., the mean PU voltage at nearest sensor, rounded to nearest 0.5 V—see *SI Appendix* for further details). *Left* graph shows responses to the question, Did your home experience voltage fluctuations in the last month? *Right* graph shows whether a participant noted voltage as a top concern when asked, What are the most severe electricity-related concerns? We note that some respondents may "normalize" the condition of uneven voltage and may therefore say they are not experiencing voltage problems. If so, the number of those who report experiencing no voltage problems may be an undercount.

and fridges that could not reliably store food. Low or extreme voltage can mean needing to replace appliances more frequently or purchase voltage stabilizers, resulting in higher costs for an already cash-constrained population. It can mean not being able to rely on appliances that have been purchased; even with a fridge a household may need to shop and cook daily, or even with an electric cooker the biomass stove cannot be retired. While those respondents who considered voltage quality a top problem tended to have top-tier appliances, even those with more common electrical appliances were impacted by poor power quality. Households from all socioeconomic strata indicated that they would consider paying more for better quality service.

Unguja is only one of many communities where resource-constrained utilities strive to provide electricity to cash-poor consumers. In Kenya, for example, an increase in the number of household connections "has been matched by an equally sharp decrease in average residential consumption" (ref. 15, p. 8). Our findings suggest that inadequate power quality on the supply side limits consumption by damaging appliances or discouraging consumers from buying others that they may wish to use. In turn, low consumption contributes to low cost recovery, potentially constraining the utility's capacity to invest in infrastructure, such as line voltage regulators or distributed energy sources sited close to the customers (29) that could deliver better power quality. This negative feedback between utility revenue and consumer demand highlights the consequences of the financial pressure that utilities and consumers face as grid systems spread (30).

Our findings reveal that power quality (or a lack thereof), measured here as voltage magnitude and variability, is an essential factor in determining the benefits that electrification can deliver. On the Unguja grid, the ability to benefit from the basic accoutrements of modern life—exactly what universal access to modern energy services aspires to provide—is not guaranteed. In the quest to attain modern energy for all, therefore, energy and development scholars must take seriously what constrained grids are actually able to offer SSA communities. While these systems undoubtedly offer increasing opportunities, they do so at present in ways that are neither adequate nor equitable.

Materials and Methods

We took a mixed-methods approach, using 62 open-ended interviews, 151 household surveys, and 2 y of voltage measurements to monitor the electric grid. Our open-ended interviews followed the grounded-theory approach (31), where interviews build upon themselves iteratively, allowing for themes to emerge and be continually coded until saturation. The majority were household interviews, with some small businesses included. Our sampling strategy was purposive (i.e., a nonrandom sample broadly selected for the characteristics of the population and the objectives of our study). It was designed to elicit a range of experiences and perceptions and to ensure broad socioeconomic and locational representation. Our structured surveys included almost all of the customers on the grid in our study locations. The surveys were distinct from, but informed by, the 62 interviews (*SI Appendix* for more information).

Because technical terms commonly used when discussing electricity are unfamiliar to everyday users, and because perceptions and experiences vary, survey terminology required "shopping around" to ensure broad understanding. With fluency in Swahili and power-systems terminology, V.J. catalogued power-quality conditions with their associated experiences. Thus, voltage fluctuations were identified as *umeme unapanda na unashuka*, which literally means "electricity goes up and down." Such language readily captures light bulbs growing brighter or dimmer and fans sounding louder or softer. We completed 151 structured surveys in sites A and B (Fig. 3 and *SI Appendix*, Tables S1 and S2). The surveys were informed by the initial 62 interviews and, after piloting, were administered by 3 local enumerators. They were completed over the course of 2 wk.

Voltage measurements were taken using 2 high-resolution power quality monitors (PQubes) at 11 homes in 5 distinct regions of Unguja during 2016 (Fig. 2). The PQubes were provided by Power Systems Laboratory (24). We then used 14 devices built specifically for the study to measure voltage in sites A and B between December 2017 and June 2018. The devices were placed strategically throughout the 2 sites. PQubes were installed at the transformers for sites A and B and were used to verify base voltage profiles for each site.

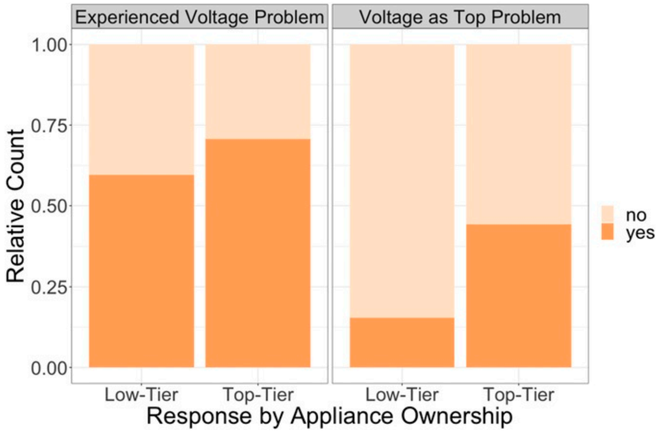

Fig. 7. Survey responses for both sites A and B related to voltage by appliance ownership. Participants are divided by low-tier electrical appliances (lights, TVs, irons) and top-tier electrical appliances (fridges, freezers, blenders).

Voltage data are available without locational identifiers through Dataverse under the project title "Power Quality and Modern Energy for All." Survey and voltage data relevant to this study are publicly available on Dataverse (32–34). The study protocol was reviewed and approved by the Institutional Review Board of University of California, Berkeley: Protocol ID: 2014-04-6289. We obtained consent from every interviewee and survey respondent after sharing information about 1) the scope of the research; 2) the voluntary nature of their willingness (or refusal) to participate; and 3) the absence of any cost, benefit, or potential risk of participation (or refusal to participate) in the study.

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