# Voltage quality and economic activity

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**Abstract**

Voltage quality concerns—such as sags, spikes, and fluctuations—are pervasive across many low- and middle income countries, yet a lack of systematic voltage data has hampered large-scale analysis of their economic importance. This paper uses state-of-the-art measurements to shed light on this component of publicly-provided infrastructure, which underpins most modern industrial, commercial, and residential activity. We combine minute-by-minute customer-level power measurements with detailed panel surveys of more than 1,500 households and small businesses in Accra, Ghana to characterize customer experiences with voltage quality issues, quantify the associated economic costs, and estimate the causal impact of a modest improvement in voltage quality as a result of quasi-random electricity grid investments. The analyses produce three main findings. First, voltage problems are ubiquitous: grid electricity is of poor quality (more than 10% below nominal voltage, 230V) approximately 20% of the time—30% during peak hours. Second, customers experience voltage-related equipment damages, purchase expensive equipment to protect against voltage problems, and are willing to increase monthly electricity spending by 10% for power supply with half of the existing voltage problems. Third, using a differences-in-differences design, we find that a 5V increase in average voltage—resulting from the construction of additional transformers at a cost of $286 per household—reduces the frequency of appliance damages but generates no other economic impacts after one year. Resource-constrained governments will need to balance the economic gains from voltage improvements against the significant cost of infrastructure investments.

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# 1 Introduction

Novel sources of spatially and temporally high-frequency data—such as satellite imagery, internet-of-things, and mobile phone records—have massively expanded the scope and precision of economic measurement in recent years. This can drive economic improvements, for example by improving the enforcement of contracts, regulations, and property rights.[1] It also enhances researchers' abilities to assess the technological determinants of economic performance. Within the electricity sector, researchers have used such data to study affordability, pricing, and formality, among other topics.[2] In this paper, we leverage the large-scale collection of spatially and temporally high-frequency power quality measurements to provide unparalleled insight into a little-understood yet core underpinning of modern energy grids: voltage quality.

In most countries, electric utilities are charged with providing electricity within ±5% of targeted voltage, so that machinery and appliances can operate efficiently and without damage.[3] Utilities in low-resource contexts often fail to meet these standards (see for example Blimpo and Cosgrove-Davies, 2019; Jacome et al., 2019; Meeks et al., 2023; and WB, 2020). However, voltage issues continue to be deprioritized in policy and regulatory debates. The United Nations (UN) Sustainable Development Goal 7—*"affordable, reliable, sustainable and modern energy for all"*—does not even mention voltage (UN, 2022). World Bank (WB) reports on energy often either do not discuss voltage or depend on self-reported data collected in households surveys, which—as we will discuss in this paper—can be imprecise (WB, 2020; WB, 2021). The WB Energy Sector Management Assistance Program (ESMAP) Multi-Tier Framework quantifies electricity access and reliability in detail (ESMAP, 2015), but only defines two coarse tiers of voltage quality: whether or not voltage problems affect appliance use.[4] Yet even this relatively narrow definition of voltage quality is difficult to measure. Understanding the economic costs of poor voltage quality and the value of voltage improvements—in particular relative to improvements in access, reliability, or affordability—is crucial in enabling resource-constrained utilities to optimally target grid investments.

This paper documents and studies the economic implications of pervasive voltage quality problems using evidence from Accra, the capital of Ghana. A key contribution of this paper is our analysis of 337 million customer-level reliability and voltage measurements collected from across more than 1,000 utility customers over the span of six years. We complement this with panel survey data from over 1,500 households and firms. We first characterize the relationship between voltage quality and economic activity, and then estimate the causal impact of a $14 million investment quasi-randomly improving electricity grid infrastructure—part of the Millennium Challenge

[1] For examples in environmental economics see Boomhower et al. (2023), Greenstone et al. (2023), and Zou (2021).

[2] On affordability: Borenstein (2012), Burgess et al. (2021), Cong et al. (2022), Lee et al. (2020), and Levinson and Silva (2022). On responsiveness to prices: Deryugina et al. (2020) and Ito (2014). On formality: Jack and Smith (2020) and McRae (2015). On access: Burlig and Preonas (2023), Dinkelman (2011), Gaggl et al. (2021), Lee et al. (2020), Lewis and Severnini (2020), and Lipscomb et al. (2013). On capacity: Burgess et al. (2021) and Ryan (2021). On availability and reliability: Abeberese et al. (2019), Allcott et al. (2016), Fisher-Vanden et al. (2015), Gertler et al. (2017), Guo et al. (2023), Hardy and McCasland (2019), and Migisha et al. (2023).

[3] As examples, nominal voltage is 120V (Volts) in the US and 230V in Ghana.

[4] For example, the 'availability' category contains five tiers for daily availability and five tiers for evening availability.

Corporation Ghana Power Compact—on electricity quality and on a wide range of socioeconomic outcomes.

The analyses generate three key findings. First, we document significant voltage problems. Average voltage at baseline is 219 volts (V), which is 11V (5%) lower than the targeted nominal level of 230V. Voltage is more than 10% (20%) below the nominal level 5.3 (1.2) hours per day. Customers experience an average of 250 'spells' each month when voltage drops at least 10% below nominal for at least two minutes, lasting more than 130 hours. Such fluctuations are likely highly damaging for commercial and residential appliances: machinery cannot operate at full capacity, and protective components malfunction causing appliances to burn.[5]

Second, these voltage issues are salient to respondents and bring economic costs. Thirty-one percent of businesses report voltage to be an important obstacle to operations, and 26% of respondents own devices to protect appliances against bad voltage, valued at $51 on average (approximately 10% of both monthly household income and monthly business revenues in the sample). Despite such investments, 27% of respondents report that at least one appliance was damaged due to bad voltage in the last year, costing an average of $39 to repair or replace.

In contexts with widespread voltage quality problems, can electricity grid investments meaningfully improve economic outcomes? Using a difference-in-differences approach, our third finding is based on grid investments at 76 sites where a new transformer was constructed relative to 75 comparable sites that did not receive such an investment. The investments increased average voltage by almost 5V and reduce the time spent with low quality voltage by 37 hours per month (with no impact on outage hours). This causes a marginally significant reduction in the ownership of protective devices and voltage-related damages. However, it has no significant impact on major household and firm socioeconomic outcomes including electricity spending, appliance ownership, business profits, and household income. This is true across respondents with different baseline levels of voltage quality and electricity dependency. Because of the lack of impact of transformer construction beyond immediate voltage-related outcomes, the costs of the investment likely exceed the economic benefits.

These null effects could be because the improvements in voltage quality were too minor to trigger significant changes in investment decisions and electricity use. Customers in treatment sites still experience 12 hours per month when voltage is more than 20% below the nominal level, and the intervention did not address the threat from voltage spikes. Further, investment in new appliances could have been hindered due to the COVID-19 pandemic or not yet realized by the time of the endline survey.

These analyses offer a framework to measure the severity of voltage problems and evaluate the impact of power distribution network improvements. Modern utilities face significant constraints and must make strategic decisions on how to allocate scarce resources within the electricity sector, for example choosing between expanding access to communities without grid connections,

[5] Elphick et al. (2013) for example state, "an argument can be made that voltage sags are the most costly of all power quality disturbances because of costs associated with lost production" (Sharma et al., 2018).

improving generation capacity to support the continuous operation of high-utilization equipment, or improving the distribution network to enhance voltage quality and power reliability. Voltage quality may matter for economic activity, but are expensive: we find limited impacts even of an investment that cost $286 per household. *Are investments in improving voltage high return?* Our project cannot provide a universal answer because power networks vary substantially. However, we develop a framework to assess this question and then apply it to a power grid in a large city in Sub-Saharan Africa where power reliability and quality problems are ubiquitous. The power monitoring infrastructure that we put in place forms a foundation to address this question. Our application, using a difference-in-differences approach in Accra, provides an important first data point by analyzing the impact of a grid investment on voltage and subsequent effects on economic outcomes.

This paper builds on a small set of research papers on voltage quality issues in low- and middle-income countries. Jacome et al. (2019) measure power quality among 25 households in rural Tanzania, finding that this is often more than 10% below nominal voltage. Meeks et al. (2023) use voltage indicators at the transformer level to study how the roll-out of smart meters affects voltage fluctuations and electricity consumption. Blimpo and Cosgrove-Davies (2019) report that one-third of surveyed enterprises in Tanzania reported appliance damage from voltage fluctuations. In a 2018 survey conducted in Cambodia, Ethiopia, Kenya, Myanmar, Nepal, and Niger, 28% of schools and health centers reported that damaged equipment due to voltage fluctuations was a constraint to operations (WB, 2020). More broadly, this paper expands our understanding of the economic impacts of infrastructure quality in low- and middle-income countries (Aterido et al., 2011; Hallegatte et al., 2019; Maruyama Rentschler et al., 2019).

Finally, our paper expands an exciting new strand of research that uses rich new sources of data to answer economic questions, such as the use of satellite imagery for understanding the economic impacts of climate change (e.g., Carleton et al., 2022), the use of mobility and location data to advance quantitative spatial economics (e.g., Redding and Rossi-Hansberg, 2017), and the use of high-frequency utility data to understand price responsiveness (e.g., Ito, 2014). Spatially and temporally granular data can allow a more comprehensive understanding of economic phenomena.

## 2 Voltage quality: importance and measurement challenges

Existing global energy policy focuses overwhelmingly on access and reliability. The World Bank (WB) quantifies these dimensions in nuanced detail, delineating 12 distinct categories of capacity and 10 categories of availability, with detailed metrics for each category (ESMAP, 2015). However, voltage is only characterized by two categories: "voltage problems that damage appliances" and "voltage problems do not affect the use of desired appliances". This very coarse categorization of what is a highly complex phenomenon may be driven by limited data availability on voltage. The lack of granular data prevents voltage quality from being adequately factored into grid planning and key economic indicators.

Utility regulators normally set a target voltage mean and range for electricity distribution, and appliances are designed to use voltage within this range. Most of the world's population—including Ghana—has a nominal voltage of 230 volts (V) (IEC, 2023). Meeting defined voltage requirements is critical to ensuring a high-quality electricity supply, which is in turn fundamental to maintaining secure and stable power systems (IEA, 2022).

### 2.1 Types of voltage quality issues

Most utility regulators limit the amount of time that voltage, as experienced by customers, can deviate from the nominal voltage level by more than ±5% or ±10%. During voltage sags—when voltage falls below the nominal range—appliances often cannot function properly. Lightbulbs will dim or flicker. Some appliances cannot be turned on, particularly if voltage falls to more than 20% below nominal. Others will experience failure of protective components, while other components continue to function, burning appliances. Voltage spikes—extreme increases often lasting only microseconds—can also cause significant damages to plugged-in appliances. These are rare but sometimes occur as power returns after an outage. Voltage surges—modest but longer-lasting increases above the nominal voltage range—are less damaging than voltage sags as well as less common. We present data on these phenomena in Section 3.

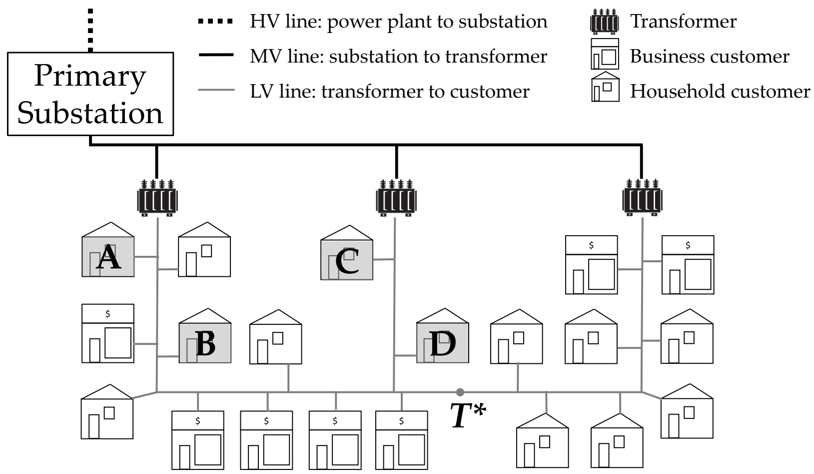
How voltage fluctuations affect appliances is complex, non-linear, and not well understood. A single short but large voltage spike or drop can cause more damage than a more moderate but lengthier voltage surge or sag, but a simple average voltage metric will not capture this non-linearity. Fluctuations may also affect appliances differently than a lengthy period of low voltage. Unlike reliability, where the System Average Interruption Duration Index (SAIDI) is a globally and industry-wide accepted indicator (NERC, 2020; Vugrin et al., 2017), there are no standard indicators for voltage quality. To provide a comprehensive picture of voltage quality, we analyze several metrics: average voltage, time spent outside of certain voltage thresholds, the count of voltage sags, the duration of voltage sags, and the intensity of voltage sags as measured by minimum voltage reached.

### 2.2 Causes of poor voltage quality

In most countries, high voltage (HV) cables transmit electricity from power stations to primary substations. Medium voltage (MV) cables then transmit this on to transformers, and low voltage (LV) distribution lines distribute power from transformers to residential and commercial customers. Figure 1 presents a schematic.

Transformer load and distance to transformer are key drivers of poor voltage quality. Transformer load is the aggregate electricity demanded by all customers connected to a transformer. When load exceeds the transformer's capacity, the transformer transmits insufficient power to meet demand, causing voltage sags. Load variability therefore also increases customer voltage variability. Distance to the nearest transformer worsens voltage due to impedance in LV lines and due to the increased load between the transformer and the customer (Jacome et al., 2019; Wolfram et al.,

Figure 1: Schematic of an electricity distribution network




Schematic of a standard electricity distribution network. Transformers step down voltage and distribute it to household and business customers along low voltage lines.

2023). The electricity grid intervention that we study (which we discuss in detail in Section 5) adds new transformers to the grid, reducing the average load on existing transformers and also reducing the distance between customers and their nearest transformer.

Figure 1 visualizes these dynamics in an example grid. Customers A and C experience similar voltage because both are near the transformer. D will experience worse voltage than C because of the increased distance to the transformer, but better voltage than B because there are fewer customers between D and the transformer than between B and the transformer. Adding a new transformer at $T^*$ should improve electricity quality for D by reducing the distance to their nearest transformer. It should also improve power for C by reducing the load on their nearest transformer.

Power outages may also affect voltage quality. In the short run, the inrush of electricity current after an outage can sometimes cause voltage spikes. In the long run, outages can degrade LV lines and increase impedance.

## 2.3 Evidence on power quality issues in low- and middle-income countries

Voltage in low- and middle-income country (LMIC) contexts often falls outside the nominal range (see Jacome et al. (2019) and Meeks et al. (2023) for examples from Tanzania and Kyrgyzstan, respectively).[6] However, a lack of large-scale data has limited research on the economic impacts of poor voltage quality. Most utilities and regulators have no way of measuring voltage as experienced

[6] Jacome et al. (2019) measure voltage quality for 25 households in Unguja, Tanzania, and find that customers near the end of the line experience experience voltage outside the nominal range around half the time. Meeks et al. (2023) analyze records for 20 transformers in Kyrgyzstan and find that they record 2.3 voltage fluctuations per day, with smart meters likely generating improvements.

by customers.[7] This problem is exacerbated in LMICs, where resource constraints prevent them from investing in improved technologies: the widespread deployment of smart meters, for example, can be prohibitively expensive (Dutta and Klugman, 2021).

Existing research therefore often turns to self-reported data. In the WB Enterprise Surveys, 20% percent of enterprises in Kenya, 39% in Nepal, and 56% in São Tomé and Príncipe report 'low or fluctuating voltage' as a constraint to operations (WB, 2020). However, self-reports are often temporally coarse: Jacome et al. (2019) and Meeks et al. (2023) ask households whether they experienced voltage fluctuations in the past month and week, respectively. Self-reports may also be unreliable because—as we show—voltage fluctuations can be difficult for customers to observe.

Poor voltage quality may impose significant economic costs, including unusable appliances, appliance damages, as well as under-investment in and under-use of electrical appliances (Jacome et al., 2019; Meeks et al., 2023; UN, 2021; Blimpo and Cosgrove-Davies, 2019). Twenty-eight percent of schools and health centers surveyed in Cambodia, Myanmar, Nepal, Kenya, Ethiopia, Niger report equipment damage due to voltage fluctuations (WB, 2020). Power quality issues push businesses to make costly investments in for example generators, voltage stabilizers, or regulators (UN, 2020; Jacome et al., 2019).

## 3 Measuring voltage quality in Ghana

Ghana achieved high levels of electricity access earlier than most sub-Saharan African countries, with 64% of households connected in 2010 compared to the regional average of 33% (WB, 2010). From 2012–2016, Ghana experienced a severe power crisis with periods of rolling blackouts in the face of power shortages. This crisis has been covered in the media (The Guardian, 2015; Al Jazeera, 2016; New York Times, 2016; BBC, 2016) and in academic research (Abeberese et al., 2019; Aidoo and Briggs, 2019; Briggs, 2021; Hardy and McCasland, 2019).[8] Access and reliability have improved significantly in Ghana in recent years, with household electricity access now 86% and outage duration down to 30 minutes per day per our data (SE4All, 2022; Kumi, 2020). Less attention has been given to voltage quality, even though Google trends for searches of terms related to voltage quality and to outages in Ghana over the last 5 years suggest they are of similar importance to customers (Figure A1).

We collaborated with engineers to deploy 1,124 GridWatch devices collecting minute-by-minute power quality data across much of the Accra metropolitan region for more than five years (Figure A2 shows a picture of the device).[9] Each device is plugged in with either a household or business connected to the electricity grid.[10] This generates 337 million data points on voltage and outages

[7] Many utilities have substation-level monitoring systems, but these only detect HV and MV outages (while LV outages can comprise a large share of power outages), and does not measure customer-level voltage. Transformer-level systems also do not capture customer-level electricity quality.

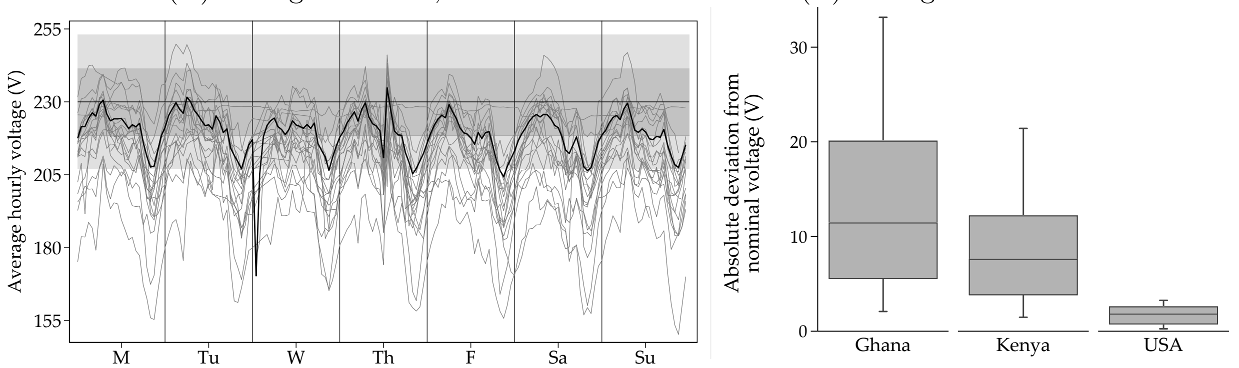
[8] At the height of the crisis, consumers faced 24-hour power cuts every 36-hour period (Mensah, 2018; Prempeh, 2020). Using data on outages at the electricity feeder (MV) level from the electricity utility in Accra, we find a peak of over 250 outage hours per month on average in July 2015, and over 100 outage hours per month for all of 2015.

[9] Klugman et al. (2019) and Klugman et al. (2021) provide more information on the technology and the deployment.

[10] Each participant receives financial compensation for each month they keep the device plugged in. Section 5

Figure 2: Customer-level voltage quality

(A) Voltage in Accra, Ghana (B) Voltage across countries




*Panel A:* Voltage measurements for 20 randomly selected participants for an arbitrarily chosen week in January 2020 (the bold line displays their average). The horizontal bands indicate ±5% and ±10% outside nominal voltage (230V). *Panel B:* 10th, 25th, 50th, 75th, and 90th percentiles of device-level voltage. Kenya data from Wolfram et al. (2023). U.S. data from Pecan Street (2018).

as experienced by households and firms. To the best of our knowledge, this is the first large-scale collection of customer-level outage and voltage data in any low- or middle-income country.

Ghana's nominal voltage is 230V. Appliances in Ghana are often rated for 220–240V, making them more vulnerable to moderate voltage fluctuations than appliances used in higher-income contexts which allow a larger input voltage range.[11] Ghana's public utilities regulator specifies that electric utilities must provide electricity with sustained voltages between ±10% of nominal, allowing for larger deviations only for very short duration (PURC, 2005).

We find that actual voltage deviates substantially from these targets. Panel A of Figure 2 displays data for 20 randomly selected devices during an arbitrarily chosen week. Several patterns are worth highlighting. First, there is significant heterogeneity in average voltage across customers. Second, customers often experience fluctuations outside the recommended range. Third, voltage is consistently worst between 7–10pm, when load is highest. Fourth, nearly all deviations outside the nominal range constitute voltage sags.

Panel B of Figure 2 compares Ghana's average absolute deviation from nominal voltage with data from Kenya (Wolfram et al., 2023) and the U.S. (Pecan Street, 2018). Voltage in the U.S. is within 3% of nominal voltage 95% of the time. In Kenya and Ghana, median voltage deviates around 10V from nominal, with Ghana often experiencing even more significant deviations.

Table 1 presents several voltage quality indicators designed to give a comprehensive picture of customer-level voltage quality. Panel A indicates that average voltage was 219V, outside the voltage rating range for most appliances in Ghana (220–240V). In a given hour, voltage was 10-20% below nominal 17% of the time and more than 20% below nominal 5% of the time on average. The

presents more information on site and respondent selection.

[11]Most modern electronic equipment is rated for input voltage between 100–240V (Elphick et al., 2013). This means that even if voltage falls to 50% (115V for a 230V nominal system), voltage is still within the operating range. However, in Ghana, few appliances are designed to function at low voltage levels. Our business and household surveys in Accra find that wide voltage ratings (such as 100–240V) for major appliances are rare. Voltage stabilizers, typically rated for 140-260V or 105-280V in Ghana, can be used to modify incoming voltage.

Table 1: Baseline measures of power quality
(A) Hourly data

| | Mean | SD | Min | $25^{th}$ | $50^{th}$ | $75^{th}$ | Max |
|---|---|---|---|---|---|---|---|
| Mean voltage during hour | 218.92 | 21.51 | 23 | 209 | 222 | 233 | 418 |
| Share of hour voltage >20% above nominal | 0.00 | 0.01 | 0 | 0 | 0 | 0 | 1 |
| Share of hour voltage 10-20% above nominal | 0.02 | 0.11 | 0 | 0 | 0 | 0 | 1 |
| Share of hour voltage 10-20% below nominal | 0.17 | 0.33 | 0 | 0 | 0 | 0 | 1 |
| Share of hour voltage >20% below nominal | 0.05 | 0.21 | 0 | 0 | 0 | 0 | 1 |
| Share of hour with no power (outage) | 0.03 | 0.15 | 0 | 0 | 0 | 0 | 1 |
| Any voltage >20% below nominal | 0.09 | 0.28 | 0 | 0 | 0 | 0 | 1 |

(B) Monthly data

| | Mean | SD | Min | $25^{th}$ | $50^{th}$ | $75^{th}$ | Max |
|---|---|---|---|---|---|---|---|
| Hours with no power (outages) | 14.24 | 14.86 | 0 | 4 | 10 | 20 | 146 |
| Number of spells with min voltage >200 | 206.96 | 243.81 | 0 | 1 | 109 | 342 | 922 |
| Number of spells with min voltage btwn 184-200 | 31.74 | 48.30 | 0 | 0 | 10 | 43 | 224 |
| Number of spells with min voltage <184 | 10.77 | 16.81 | 0 | 0 | 2 | 16 | 97 |
| Total duration of spells with min voltage >200 | 15.43 | 17.89 | 0 | 0 | 8 | 27 | 70 |
| Total duration of spells with min voltage btwn 184-200 | 31.10 | 42.76 | 0 | 0 | 8 | 52 | 181 |
| Total duration of spells with min voltage <184 | 84.15 | 160.12 | 0 | 0 | 0 | 79 | 641 |

Summary statistics for different measures of power quality from March 2019-November 2020 before transformer injection activities were completed, calculated using data from 441 GridWatch devices deployed across 138 sites. Outages are identified at the site level using data from all devices in a site. Panel A includes 2,872,508 device-hour observations, computed from thirty 2-minute observations in each hour. Panel B includes 6,871 device-month observations, taking the sum of hourly values by device within each month for the first four rows, and taking sums across individual low-voltage spells recorded by device within each month for the remaining rows.

fraction of time more than 10% below nominal exceeds 30% during peak load. Voltage sags are significantly more common than power outages, which occur 2.5% of the time (18 hours per month).

Panel B presents data aggregated to the monthly level, which enables a characterization of the frequency and duration of periods with low voltage. Consider low voltage events in which the minimum voltage fell to 184–200V, which is outside the voltage ratings for most appliances in Ghana. On average, customers experienced 32 such spells per month, lasting a total of 31 hours. For more severe spells where the minimum voltage was less than 184V (more than 20% below nominal), customers experienced on average 11 such spells per month, lasting a total of 84 hours. More extreme voltage sags are concentrated among customers with the worst power quality: the median customer experienced 10 hours of outages and 16 hours of low voltage per month.

## 4 Self-reported economic costs of poor voltage quality

Voltage quality can affect economic productivity and well-being in four main ways. First, poor voltage can restrict the productive use and utility of electric appliances. Second, it can damage appliances and require spending on repairs or replacements. Third, it can require investments in

Table 2: Baseline correlates of power quality and reliability

| Independent variable | N | Mean (SD) | Monthly hours voltage >10% below nominal | Monthly hours of outage |
|---|---|---|---|---|
| Baseline distance to transformer (100m) | 1575 | 2.43 | 33.41*** | 0.87** |
| | | (0.92) | (12.27) | (0.43) |
| Shares electricity meter with other users | 1575 | 0.40 | -1.73 | 1.36*** |
| | | (0.49) | (12.08) | (0.48) |
| Wealth index (normalized) | 1575 | -0.14 | -4.11 | -0.58*** |
| | | (0.98) | (7.55) | (0.20) |
| Household members | 746 | 3.62 | 5.15 | 0.14 |
| | | (1.91) | (3.88) | (0.13) |
| Total household monthly income (USD 100s) | 714 | 3.62 | -0.22 | -0.06 |
| | | (5.02) | (1.62) | (0.05) |
| Number of workers | 829 | 1.97 | -0.26 | -0.10 |
| | | (2.04) | (3.62) | (0.13) |
| Total revenue in past month (USD 100s) | 723 | 4.39 | -1.08 | -0.05 |
| | | (6.59) | (1.00) | (0.04) |
| Outcome mean | | | 172.38 | 14.06 |

Univariate correlations between power quality (from GridWatch devices deployed near survey respondents)—and survey respondent characteristics. All regressions control for respondent sex, age, type (household or business), and rental or ownership status. The wealth index includes roof and wall material quality, count of owned appliance types, and secondary education completion. SEs clustered by site. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

devices designed to protect against voltage fluctuations (such as voltage stabilizers) or in backup energy sources. Finally, these three mechanisms may furthermore lower long-term investment by lowering the expected value of appliances.

To study these effects, we survey 1,575 electricity grid customers—746 households and 829 businesses—across 151 distinct study sites in Accra where GridWatch devices were deployed.[12] The descriptive analyses use baseline surveys conducted in March–April 2021.

Per data from the Ghana Statistical Survey, respondents are representative of households and businesses in the Accra Metropolitan Area (Table B1). The most common business activities are small retail operations (44%), personal care services such as hair and nail care (16%), manufacture and repair of clothing (15%), and food and beverage services (5%). Businesses in the survey sample are primarily micro-enterprises with one or two employees including the owner or manager, and consequently employees, revenues, and profits are somewhat lower than the Accra median.

### 4.1 Correlates of customer-level power quality and reliability

Table 2 documents correlations between connection quality and socioeconomic characteristics. The prevalence of poor quality voltage cuts across wealth and income: monthly hours with low voltage do not vary significantly by wealth, income, or revenue. The only characteristic correlated with

[12] As we discuss extensively in Section 5, these sites are the locations of potential new transformers. To avoid survey fatigue, there is no overlap between study participants who received a GridWatch device and survey respondents.

Table 3: Baseline household and business electricity quality issues

| | Mean | SD | Min | $25^{th}$ | $50^{th}$ | $75^{th}$ | Max | N |
|---|---|---|---|---|---|---|---|---|
| *Panel (A) Experience with outages and voltage* | | | | | | | | |
| Reported number of outages in past month | 6.81 | 4.70 | 0 | 4 | 6 | 8 | 26 | 1575 |
| Reported total outage hours in past month | 39.36 | 47.60 | 0 | 12 | 25 | 48 | 300 | 1575 |
| Reported hours of bad voltage in past month | 47.49 | 92.53 | 0 | 0 | 15 | 60 | 600 | 1566 |
| *Panel (B) Economic impacts* | | | | | | | | |
| Any appliance damaged by voltage in past year | 0.27 | 0.44 | 0 | 0 | 0 | 1 | 1 | 1575 |
| Amt spent on burnt/broken apps in past year | 38.95 | 60.29 | 0 | 0 | 14 | 49 | 237 | 411 |
| Any voltage protective device | 0.26 | 0.44 | 0 | 0 | 0 | 1 | 1 | 1575 |
| Value of voltage protective devices | 50.76 | 70.36 | 2 | 16 | 26 | 61 | 560 | 220 |
| Uses an alternative energy source | 0.05 | 0.22 | 0 | 0 | 0 | 0 | 1 | 1575 |
| Outages are obstacle to business | 0.92 | 0.27 | 0 | 1 | 1 | 1 | 1 | 806 |
| Voltage fluctuations are obstacle to business | 0.31 | 0.46 | 0 | 0 | 0 | 1 | 1 | 806 |
| *Panel (C) WTP for improved service quality* | | | | | | | | |
| Max monthly WTP for perfect reliability | 3.42 | 4.51 | 0 | 0 | 2 | 5 | 21 | 1575 |
| Max monthly WTP for half of curr. outages | 1.64 | 2.80 | 0 | 0 | 0 | 2 | 18 | 1575 |
| Max monthly WTP for half of curr. volt. fluc. | 1.88 | 3.48 | 0 | 0 | 0 | 2 | 18 | 425 |
| Share of govt. investment to reducing outages | 0.17 | 0.12 | 0 | 0 | 0 | 0 | 1 | 1061 |
| Share of govt. investment to improving voltage | 0.15 | 0.13 | 0 | 0 | 0 | 0 | 1 | 1061 |

Values are in USD. Spending on burnt appliances is among those reporting any voltage-related damage. Value of voltage protective devices are among those with any such devices. Voltage protective devices include general purpose voltage stabilizers and more specialized devices such as fridge guards and TV guards. Alternative energy sources include generators, solar panels, and wet cell batteries. Only a subset of respondents in the baseline survey were asked their WTP for reduced voltage fluctuations.

voltage quality is distance to the nearest transformer: being 100 meters farther away is associated with 33 more hours (19%) of low voltage per month (Figure A3 shows this relationship graphically). This aligns with the causes of poor voltage quality discussed in Subsection 2.2.

In the case of outages, wealth is correlated with electricity reliability. A one standard deviation increase in the wealth index (proxied by structure quality, appliance ownership, and education) is associated with a 0.6 hour (4%) reduction in outages per month. Respondents who share their electricity meter—likely to be less wealthy—experience 1.4 (10%) more outage hours per month. This could reflect either customer sorting on attributes, utility investment in higher-revenue areas, or a causal effect of power quality on wealth. On the other hand, the lack of a similar relationship for voltage may indicate that voltage quality is difficult to observe for potential residents, or utilities may not be precisely targeting voltage improvements.

## 4.2 Customer self-reports of power quality and reliability issues

Table 3 reports summary statistics for households' and businesses' experiences with electricity issues. Respondents reported 39 hours of power outages and 47 hours with bad voltage over the past month on average. Self-reported outages correlate strongly with GridWatch-measured outages

(Figure A4), but respondents still under-report actual outages by more than half. There is a much weaker correlation for voltage, with customers under-estimating the frequency of low quality voltage by an order of magnitude. Individuals may only be able to detect voltage problems when voltage drops farther below the threshold of 10% below nominal voltage we use to define low voltage with the GridWatch data. They may also not observe voltage issues during periods they are not actively using appliances that are sensitive to voltage.[13] This may also be driven by measurement error in voltage quality, which varies moderately across customers within a site.

Panel B shows that poor power quality has economic costs. 27% of respondents report experiencing damages to appliances due to voltage issues in the past year. These respondents spent $39 on repairs or replacements (around 3 months of average electricity spending, or around 10% of monthly household income and business revenue). To protect against these damages, customers often purchase equipment that protects appliances from bad voltage: 26% of respondents have at least one voltage protective device, with an average estimated value of $51.[14] 92% (31%) of businesses report that outages (voltage fluctuations) are an obstacle to business operations. Just 5% of respondents have an alternative energy source (generators, solar panels, or wet cell battery): most have no alternative when grid electricity service is poor.

### 4.3 Political bias in electricity quality recall

Self-reports may be imprecise because reliability and voltage quality are significantly more difficult to observe than other publicly provided goods such as roads or schools. This enables politicians or media outlets that are politically in favor (in opposition) of the elected government to over-report (under-report) power quality. To the extent that respondents consider such information when forming beliefs about power quality, self-reports can correlate with a respondent's political preference.

To examine this, we ask respondents two questions about the government's performance, and then ask enumerators to (privately) assess the respondent's political preference. This yields a binary indicator of whether the respondent appears to support the current government or not. We examine whether this is correlated with self-reports of power quality, controlling for power quality and including a site fixed effect as power quality is more likely to be arbitrary within a site.

Table 4 presents the results. Respondents who support the government report fewer outages and fewer hours of bad voltage. In theory, this could reflect a causal effect of power quality on political support: respondents may attribute good power quality to government efficacy, and this may increase government support. However, we see no correlation between government support and power quality as measured by the GridWatch devices (Table B2). Instead, respondents may consume information provided by media representatives or politicians aligned with their political preferences, and these actors share biased information. This underscores the importance of objective

[13] Flickering of lights and appliances not turning on are key indicators of bad voltage, but they only occur when voltage sags significantly beyond 10% below nominal voltage and will be most visible at night.

[14] These include general purpose voltage stabilizers (15% of customers) as well as more specialized devices such as fridge guards (11%) and TV guards (4%).

Table 4: Political affiliation and power quality perceptions

| | Hours of outages | | | Hours of bad voltage | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Government support (=1) | -3.0 | -3.5 | -6.4*** | -1.4 | -1.5 | -9.9* |
| | (2.2) | (2.2) | (2.3) | (5.2) | (5.1) | (5.0) |
| Monthly outage hours (GW) | | 0.5*** | | | | |
| | | (0.2) | | | | |
| Monthly bad voltage hours (GW) | | | | | 0.1*** | |
| | | | | | (0.0) | |
| Observations | 1565 | 1565 | 1561 | 1557 | 1557 | 1553 |
| Mean among Govt=0 | 6.7 | 6.7 | 6.7 | 47.6 | 47.6 | 47.7 |
| Site FE | | | Yes | | | Yes |

All regressions include week FE. 139 of 149 sites have at least one respondent who reports supporting the current governing party and one who does not. Columns (2) and (5) control for the information collected by the GridWatch devices. Columns (3) and (6) include site fixed effects, as within-site variation in power quality is more arbitrary.

data to complement self-reported data.

### 4.4 Relative value of reliability and voltage quality improvements

Would customers prefer a utility to invest in reliability or voltage improvements? We find through a series of stated preference exercises that customers place significant value on reducing voltage problems, on par with the value they place on avoiding outages.

First, we use a standard set of stated preference questions to measure willingness to pay (WTP) for improvements in the reliability and quality of their electricity connection. We use a binary search to determine the maximum increase in monthly electricity costs the respondent is willing to pay for an improved connection (beyond what they spend on the electricity they consume), first asking about a randomly chosen price and then iteratively asking about either higher or lower prices based on the prior response.[15] Panel C of Table 3 shows that respondents are willing to pay on average an additional \$3.4 per month (an 18% increase in electricity spending) for access to an electricity connection with no voltage fluctuations or outages (this includes around 50% of respondents who had a WTP of \$0). WTP for a connection with no voltage fluctuations and half the respondent's baseline monthly outages and WTP for a connection with no outages and half the baseline level of voltage fluctuations are similar—\$1.6 and \$1.9 per month, respectively, representing around 10% of monthly electricity spending (Figure A5 presents the full distributions).

We also ask respondents how they would prioritize the allocation of hypothetical government funds across five different potential investment areas: reduced power outages, improved voltage quality, improved schools, reduced traffic congestion, and improved access to piped water. Around one-third of respondents report that they would evenly split the allocation across the five areas. Excluding these, respondents would on average allocate 15% of the funds to improving voltage

[15]This methodology has been used in Ghana and elsewhere in Africa—see for example Abdullah and Jeanty (2011), Berkouwer et al. (2022), Deutschmann et al. (2021), and Sievert and Steinbuks (2020).

quality, similar to the mean amount allocated to reducing outages (17%). Improving schools (29% of the funds) and access to piped water (26%) are the relative priorities.

Taken together, the results indicate that respondents value voltage improvements similarly to outage reductions. Ghana's challenges with electricity reliability—and the associated economic costs—are well-publicized (Guardian, 2015; Al Jazeera, 2016; New York Times, 2016; BBC, 2016). The fact that we find similar stated valuation of improvements in voltage quality as in reliability indicate that poor voltage quality may impose costs of a similar magnitude.

# 5 Identifying the causal impact of grid voltage investments

In 2014, the Millennium Challenge Corporation (MCC) signed the Ghana Power Compact to disburse $316 million in funding towards electricity network improvements in Ghana (MCC, 2014). $14 million was spent on low-voltage (LV) line bifurcation in the Achimota, Dansoman, and Kaneshie districts of Accra, Ghana.[16] This corresponds to expenditures of around $286 per household in these districts. We estimate the effects of this investment on power quality and economic outcomes using a difference-in-differences strategy.

## 5.1 Low-voltage line bifurcation

Line bifurcation involves adding a new transformer to the LV network with the goal of reducing average transformer loads as well as "to reduce the length of the low voltage circuits to ensure they do not exceed a length that affects the quality of service and a technical loss threshold" (MCC, 2014). Panel A of Figure 3 provides an illustration. As discussed in Subsection 2.2, the reduction in distance and in transformer load should increase average voltage and reduce voltage variance, in particular for customers whose distance to the nearest transformer decreases the most.[17]

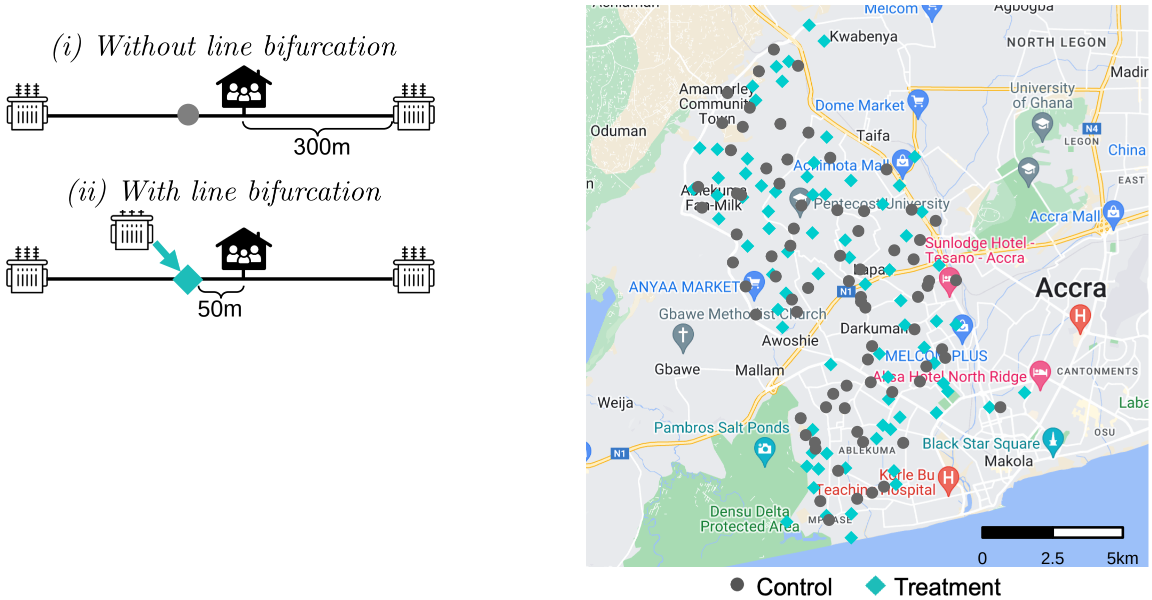
An MCC contractor selected new transformer locations within each district and then completed transformer construction. The contractor selected locations from segments on the grid that were approximately 200 to 300 meters from the nearest transformer. Other than this, they had very limited local data to inform location decisions. They did not have access to any type of socioeconomic or demographic characteristics, or utility data on things like the number metered connections, bill payment rates, or electricity demand (sub-district electricity data in general is largely unavailable as the utility only prepares district-wide data). The one exception to this is that the contractor obtained analog readings of transformer-level load measuring the highest instantaneous load experienced at a transformer since the last reading. However, these must be reset manually and are not reset at a fixed schedule, and are therefore a crude and noisy measure of load. We therefore argue that, conditional on distance to the nearest transformer, line bifurcation treatment sites were selected without obvious regard for the outcomes we study.

[16] The original amount was $498 million but this was reduced to $316 million in 2019 (MCC, 2022).

[17] In the long term, customers may respond to improved electricity quality by increasing usage, which would worsen voltage quality. This should be outweighed by the reduction in transformer load in the short term.

Figure 3: Line bifurcation control and treatment sites across Accra

Panel (A) Panel (B)




Panel A presents a schematic of control and treatment sites. Without line bifurcation, the customer is 300 meters from their nearest transformer. With line bifurcation, the distance to the nearest transformer for this customer drops to only 50m. Panel B presents a map of control and treatment sites across Accra, Ghana.

The contractor selected 76 locations for transformer injection ('treatment sites') in the three study districts. Using spatial data covering the entire electricity network in Accra, our research team identified segments of the LV grid that were between 200 and 300 meters from both any existing transformers and the planned new transformers—thus following the main criterion for treatment site selection—and then randomly selected 75 locations from this set as control sites (Panel A of Figure A10 shows that the distribution of distances to the nearest existing transformer is similar for treatment and control sites). The 76 treatment sites and 75 control sites, shown in the map in Panel B of Figure 3, comprise the 151 sites of our study sample.

We then use maps of the distribution network to define the boundaries of each site (Figure A6 presents an example). We first identify segments of LV lines that are <200 meters from the site but >300 meters from any existing transformers. Customers within 25 meters of these LV segments are those whose electricity service would likely be affected by a transformer injection. Defining these boundaries also reduces the likelihood of spillover voltage improvements in control sites from nearby transformer injections (we find no evidence that control sites located near treatment sites experienced power quality improvements; see Table B3).

### 5.2 Data

GridWatch devices began collecting voltage quality and reliability data at all sites by March 2019 (see Klugman et al. (2019) for more detail on the deployment methodology). We focus on data collected between March 2019 and April 2023, encompassing the transformer construction period which lasted from October 2020 to March 2021 (Figure A7 presents a timeline).

Baseline surveys with 6-7 businesses and 6-7 households in each site were conducted in March–April 2021 and endline surveys in July–September 2022.[18] There is no overlap between the set of respondents that received a GridWatch device and the set of survey respondents.[19]

To lend support to the quasi-random nature of the assignment mechanism, we conduct a battery of tests examining baseline differences between control and treatment sites. Levels and pre-trends in outages and voltage by site treatment status are statistically indistinguishable before the line bifurcation intervention (see Panel A of Figure 4 and Panels A and B of Figure A8). Levels and trends in nighttime radiance data from VIIRS are also nearly identical prior to the intervention (Figure A9). Respondents' socio-economic characteristics at baseline are balanced across treatment and control sites (Table B1).[20] The distributions of distance between each survey respondent and the nearest existing transformer prior to line bifurcation are statistically indistinguishable across control and treatment sites (Panel A of Figure A10).[21] This evidence of baseline balance and parallel pre-trends, in conjunction with the quasi-random institutional design of the line bifurcation investments, support the logic that a difference-in-differences design will identify the causal impacts of these electricity grid improvements.

Of 2,001 respondents surveyed at baseline, 1,575 were surveyed at endline. Attrited respondents are similar to non-attrited respondents in terms of treatment status and along most socioeconomic characteristics (Table C1), though they differ along a small number of variables commonly associated with attrition such as age, household size, and rental status (Table C2).

To verify compliance with planned transformer injections, we use progress reports submitted by the private contractor tracking construction progress at each site. In addition, we conducted site visits in November 2020, January 2021, and October 2021 to confirm the presence (absence) of new transformers at treatment (control) sites.

### 5.3 Results: Impact of line bifurcation on power quality

Figure 4 plots average voltage by hour of day and by treatment status before and after construction of new transformers. Panel B shows that the intervention increased average voltage by around 5V in treatment sites relative to control sites across all hours of the day. As a result, average voltage in treatment sites is within ±5% of nominal voltage across all hours of the day after treatment.

Figure 5 illustrates the distribution of effects across treatment and control sites. Green areas

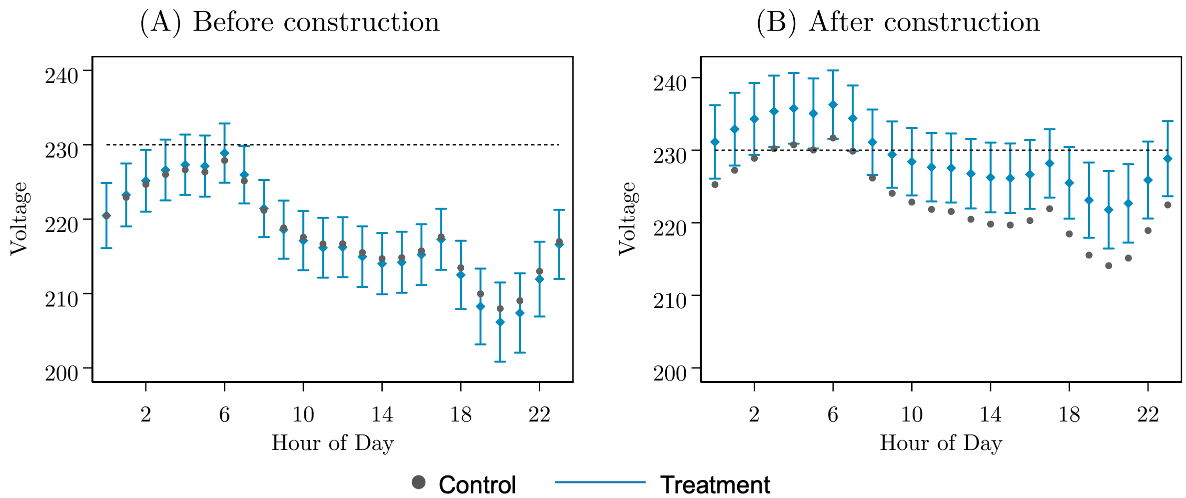
[18]Due to COVID-19-related delays, baseline surveys were conducted while line bifurcation construction activities were being completed. However, voltage quality did not improve significantly until April 2021 (Figure A8). And, the short period between construction and baseline surveys is likely to have been too short for households or businesses to notice any sustained improvement, let alone act on this improvement and have it reflected in socioeconomic outcomes—most of which are measured over the month or year prior to the survey date. In support of this, we find no baseline differences in respondent outcomes by treatment status (Table B4).

[19]For the analysis, each survey respondent is matched with the outage data for the site they are located at (as outages are detected at the site level) and the voltage data from the GridWatch device nearest to their location.

[20]The p-value for a joint F-test for household characteristics is 0.185, while that for business characteristics is 0.442.

[21]Prior to construction, respondents at control (treatment) sites are on average 233 (253) meters from the nearest transformer (see Figure A10 for the full distribution).

Figure 4: Impacts of transformer injection on voltage by time of day




Average voltage by hour of day and treatment status with 95% confidence intervals around treatment means. The dashed line shows Ghana's nominal voltage (230V). Average voltage increases by 5V in control sites and by 10V in treatment sites after construction. SEs clustered by site. Figure C1 shows impacts on outage duration.

indicate the fraction of time electricity fell within ±5% of nominal voltage on average during the pre-construction period, by site. Yellow areas below (above) the green areas indicate deviations of between 5–10% below (above) nominal voltage. Red areas below (above) the yellow areas indicate deviations of at least 10% below (above) nominal voltage. Black areas indicate outages. The graphs show the distribution separately for each site, ordered by time spent with power more than 10% below nominal voltage.

The main effect of the intervention was to reduce the time where voltage was more than 10% below nominal voltage, though average time between 5-10% below nominal also fell. It also increased the amount of time when voltage was more than 5% *above* nominal voltage, but as discussed in Subsection 2.1 small deviations above nominal voltage are unlikely to negatively affect appliances. The increase in average voltage thus largely protects customers from voltage sags, which are most likely to damage appliances and affect use.

To estimate the treatment effect formally, we use a panel fixed effects regression:

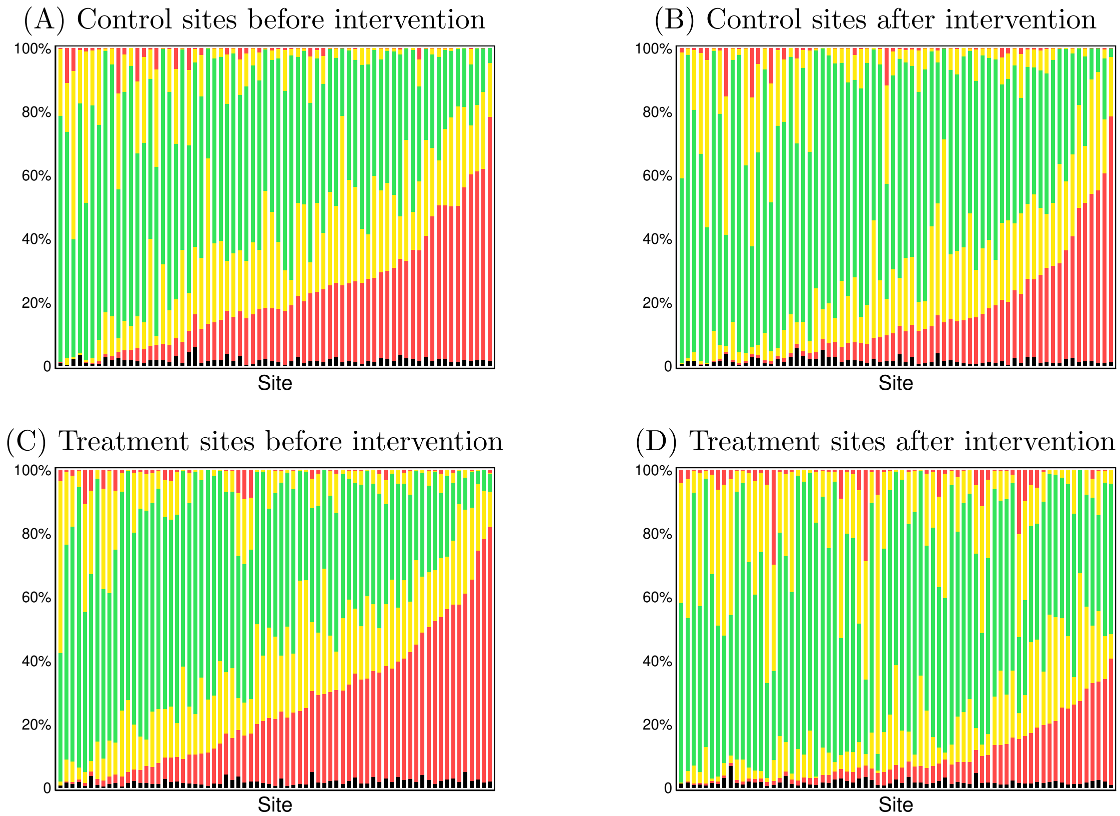
$$Y_{it} = \beta_0 + \beta_1 \text{Post}_t + \beta_2 \text{During}_t + \beta_3 \text{Treat X Post}_{it} + \beta_4 \text{Treat X During}_{it} + \boldsymbol{\Gamma_s} + \boldsymbol{\Gamma_t} + \epsilon_{it} \tag{1}$$

Where $Y_{it}$ is an outcome experienced by device $i$ at time $t$. $\boldsymbol{\Gamma_s}$ are site fixed effects, which subsume the 'Treat' dummy. $\boldsymbol{\Gamma_t}$ are time fixed effects that vary across regressions. $\beta_1$ and $\beta_2$ capture changes in voltage levels after and during construction relative to the pre-construction period. $\beta_3$ captures the treatment effect of interest.[22] Standard errors are clustered by site in all regressions.

Table 5 presents the results. Columns (1) and (2) use hourly data to estimate the impact of

[22]Event study results showing impacts by quarter are shown in Panels C and D of Figure A8.

Figure 5: Impact of transformer injection intervention on distribution of grid quality




Distribution before and after transformer injection at control sites and at treatment sites. The black area represents power outages. Green areas indicate the fraction of time voltage was within ±5% of nominal voltage. Yellow areas indicate ±5-10% while red areas indicate a greater than ±10% deviation from nominal voltage.

line bifurcation on minutes of power outages and on average voltage.[23] The transformer injection intervention increased average voltage by 5.5V relative to control sites, but had no impact on power outages. Columns (3) and (4) use monthly data to estimate the impact on low-voltage spells (periods during which voltage drops at least 10% or 20% below the nominal level).[24] The treatment caused a 37 (28) hour decrease in the monthly hours of spells with voltage more than 10% (20%) below nominal, respectively. This represents a 51% decrease in the most severe low-voltage spells.

Line bifurcation decreases the likelihood that voltage falls more than 20% below nominal voltage in a given hour by 4 percentage points (50% relative to the control mean); time spent below this threshold falls by 1.4 minutes per hour, or 51% (Table C5 and Table C6). Time spent between 10–20% below nominal voltage decreases by 4 minutes per hour in treatment sites relative to control sites (44%). The number of low-voltage spells per month falls by 46 in treatment sites relative to control sites, a 25% decrease relative to the pre-construction control mean. Relative impacts are again largest for the most severe spells. These effects translate into a significant reduction in

[23]Results are similar in alternative specifications considering ways in which transformer injection implementation deviated from initial plans (Table C3, Table C4).

[24]Results are qualitatively unchanged when instead using week-of-sample or day-of-sample fixed effects, which also subsume the 'Post' and 'During' dummies, and when dropping the site fixed effects.

Table 5: Impact of transformer injection intervention on outages and voltage

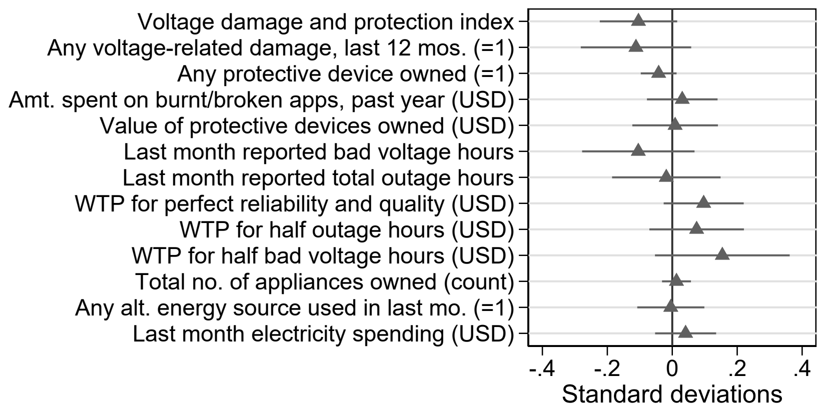
| | (1) Minutes power out per hour | (2) Average voltage | (3) Monthly hours of spells (voltage >10% below nominal) | (4) Monthly hours of spells (voltage >20% below nominal) |
|---|---|---|---|---|
| During construction | 0.21*** | 0.76 | 7.27 | 5.05 |
| | (0.07) | (1.09) | (8.77) | (7.42) |
| Treat X During | -0.06 | 2.38 | -21.63 | -20.92* |
| | (0.12) | (1.60) | (13.52) | (11.45) |
| Post construction | -0.08 | 5.94*** | -22.57** | -17.79** |
| | (0.08) | (1.75) | (11.11) | (8.70) |
| Treat X Post | -0.21 | 5.48** | -37.22** | -28.62** |
| | (0.13) | (2.48) | (15.40) | (12.26) |
| Observations | 10033086 | 9866078 | 19079 | 19079 |
| Pre-construction control mean | 1.39 | 219 | 91.9 | 56.1 |
| Hour of day FE | Y | Y | N | N |
| Week of year FE | Y | Y | N | N |
| Month of year FE | N | N | Y | Y |
| Site FE | Y | Y | Y | Y |
| Hourly/monthly data | Hourly | Hourly | Monthly | Monthly |

Difference-in-difference results for the impact of treatment on power quality measured by GridWatch devices. Columns (1)-(2) use hourly data while Columns (3)-(4) use monthly data. Standard errors are clustered at the site level. Table C5 and Table C6 show additional outcomes. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$

the *severity* of low-voltage spells in treatment sites post-construction relative to control sites: the longest spell in a month is 4.5 hours shorter and mean voltage during low-voltage spells is 14V higher. These results show that line bifurcation caused voltage improvements at both the extensive and the intensive margin.

It is worth noting that Figure 4, Table 5, and Figure 5 also show voltage quality improvements over the study period at control sites. Average voltage at control sites post-construction is within ±5% of nominal voltage at all hours except during peak load hours (Figure 4). An event study version of this analysis shows that voltage gains in treatment sites relative to control sites were stable for a year after construction completion, but decreased slightly and were no longer significantly different from 0 after around 18 months (Panel C of Figure A8). These improvements do not appear to be due to spatial spillovers from nearby treatment sites: the voltage improvement at control sites does not differ significantly by distance to the nearest treatment site (Table B3). Furthermore, line bifurcation did not significantly change distances to the nearest transformer in control sites (Panel B of Figure A10), and combining changes in control site device distances to the five nearest transformers at endline with how those distances correlate with average voltage suggests this would only explain a small share of the control site increase in voltage post-construction. Voltage improvements in control sites may be due to other large-scale MCC investments in the grid at the time under the Ghana Power Compact, or to changes in electricity consumption due to COVID-19 or other economic forces.

Figure 6: Impact of transformer injection treatment on electricity-related survey outcomes




Coefficients and 95% confidence intervals from Equation 2, pooling business and household respondents. Standard deviations relative to the baseline control mean. The voltage damage and protection index composes 'any voltage-related damage' and 'any protective device owned'. Table B4 shows non-normalized outcomes.

## 5.4 Results: Impact on customer electricity experiences

We estimate impacts of the line bifurcation treatment on self-reported outcomes using the following difference-in-differences specification:[25]

$$Y_{it} = \beta_0 + \beta_1 \text{Post}_t + \beta_2 \text{Treat}_i + \beta_3 \text{Treat X Post}_i + \boldsymbol{X_i} + \epsilon_{it}, \tag{2}$$

For outcome $Y_{it}$ experienced by respondent $i$ at time $t \in \{0, 1\}$. $\beta_3$ captures the differential outcome being observed post-construction in treatment sites—the treatment effect of interest. $\boldsymbol{X_i}$ are baseline socioeconomic controls (age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is a household or a business, and district fixed effects). Standard errors are clustered by site in all regressions.

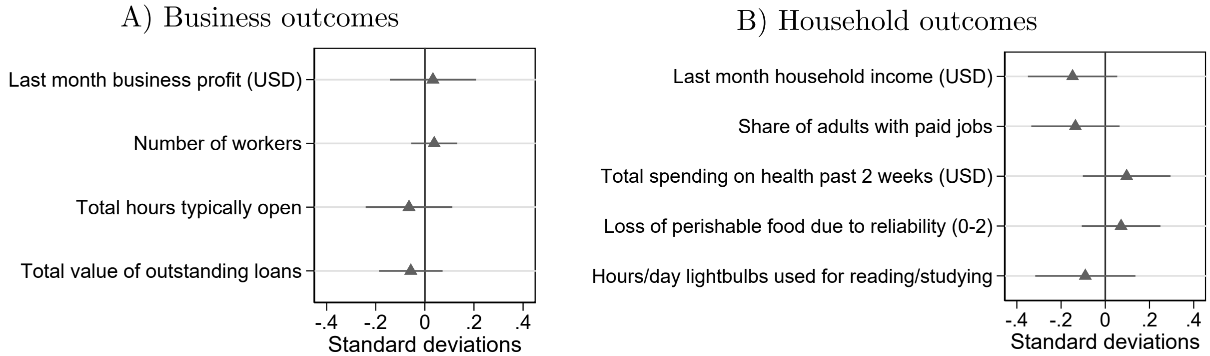
Figure 6 presents impacts on electricity outcomes, normalized around the baseline control mean, pooled for businesses and households.[26] We estimate a 0.1 SD reduction ($p$=0.09) in a voltage damage and protection index comprised of two components: whether appliances were damaged by voltage in the past year and whether the respondent has any voltage protective device. The point estimates for the two components are not individually statistically significant but are both negative, and imply a 20% decrease in voltage-related damages.

We see no differences between treatment and control for any other electricity-related outcomes. This may have been because treatment coincided with broader voltage quality and quality improvements across Accra. The probability of having had an appliance damaged by voltage issues over the past 12 months, ownership of voltage protective devices, and WTP for improved electricity connections all fall across all sites after construction, and self-reported daily hours of bad voltage at

[25]This specification was registered in our pre-analysis plan (Berkouwer et al., 2019). Voltage improvements were unanticipated so voltage-related analyses were not detailed in the pre-analysis plan.

[26]Table C7 shows additional outcomes for businesses. Results and discussion for all other outcomes listed in the pre-analysis plan are included in Appendix D.

Figure 7: Impact of transformer injection treatment on primary socio-economic outcomes




Coefficients and 95% confidence intervals from Equation 2. Standard deviations relative to the baseline control mean. Table B5, and Table B6 show non-normalized outcomes for Panels B and C, respectively.

control sites was nearly zero during the endline (Table B4).[27] Seventy-one percent of respondents at endline say voltage is much better than two years ago (19% say it is slightly better), and businesses are 19 percentage points less likely to say bad voltage is an obstacle to business operations at endline compared to baseline. Respondents report improvements in electricity quality and significant decreases in voltage damages, costs, and protective device ownership after the construction period. WTP for improved electricity connections also falls on average in the post period. The voltage improvements at control sites may have been sufficient to resolve many voltage issues observable to customers. Use of alternative energy sources such as generators and solar panels was low at baseline and did not change over time.

### 5.5 Results: Impact on socioeconomic outcomes

Panels A and B of Figure 7 show no treatment impacts on a wide range of business and household outcomes, respectively (Table B5 and Table B6 present these and additional outcomes).[28] These results indicate that voltage quality improvements may not lead to more meaningful impacts on socioeconomic outcomes.

What can explain this? First, the investment may not have caused a sufficiently large increase in power quality to have a detectable impact on socioeconomic outcomes. The improvement in voltage that control sites experienced after line bifurcation may have been enough to address the most severe voltage issues, such that there was little socioeconomic benefit from the additional improvements at treatment sites. These changes may be due to reduced concerns and restrictions related to the COVID-19 pandemic, or seasonal differences in energy use and economic activity due

[27] This is consistent with seasonal trends in average voltage levels: voltage is typically better in July-September, which coincides with the endline survey (Panel A of Figure A8). Similar seasonal trends explain a large decrease in self-reported outage hours between baseline and endline in control sites, which is not consistent with the non-significant effect of construction on outage hours as measured using GridWatch devices.

[28] There was a significant reduction in business expenditures in the past month of 0.22 SD ($98, $p = 0.049$), however there was also a modest reduction in reported revenues of 0.14 SD ($87, $p = 0.14$), such that there is no aggregate effect on profit. The effects on business costs furthermore do not survive False Discovery Rate (FDR) adjustment for multiple hypothesis testing (Table C8). We therefore attribute this result to statistical noise.

to the differences in the timing of the two surveys. Decreases in average monthly business profits, household incomes, and electricity spending measured in USD are also partly due to high levels of inflation in Ghana at endline relative to baseline—differences in Ghana Cedis are smaller.

In addition, chronically low-quality and unreliable electricity may cause customers to have a limited stock of electric appliances: customers may only benefit from improved voltage in the longer term, after they increase or improve their stock of appliances. We observe no difference in appliance acquisition after construction by treatment status: 37% of respondents at endline in both sites reported acquiring at least one new appliance since the baseline survey, with no difference between businesses and households (Figure A11). Many of these appliances replaced others already held such that the mean total count of electric appliances did not change significantly between baseline and endline.

Finally, voltage may be less important to economic activity, or impacts of average voltage may be non-linear, with larger marginal effects for increases at low levels of voltage.

### 5.6 Heterogeneous effects

We find no statistical differences in the impact of line bifurcation on socioeconomic outcomes by baseline voltage quality, defined as being above or below the median daily hours of voltage within 10% of nominal average (Column 1 of Table B7), despite the fact that treatment sites with below-median baseline voltage experienced greater voltage improvements (Table B8). This suggests that the lack of impacts was not driven by respondents whose power quality was already within an acceptable range at baseline. We also evaluate heterogeneity by baseline characteristics that reflect the importance of voltage quality for respondents, including reported electricity importance (for businesses), willingness to pay for perfect electricity reliability and quality, and ownership of protective devices. Again, we find no significant differences (Columns 2–4 of Table B7). The modest improvements in voltage quality due to transformer injection have no impact on socioeconomic outcomes regardless of their baseline voltage experiences and of how important electricity is to them according to their baseline responses.

### 5.7 Robustness

The results are robust to different measures of where and when planned transformer construction was completed (Table C3, Table C4, and Table C9) to address possible measurement error in construction timing.[29] To address any potential SUTVA violations, we drop control sites closer to treatment sites than median (1.3km) (Table C10). We also drop 'movers' and anyone for whom the monotonicity assumption on distance to the nearest transformer is violated (not shown). None of these robustness tests qualitatively change the results (Appendix C).

[29] We drop two treatment sites where the contractor indicated that the transformer was not commissioned and drop additional treatment sites where additional construction monitoring found no new transformer constructed. We also run an instrumental variables version of this regression, using treatment assignment as an instrument for new transformer construction.

As a back of the envelope check, higher voltage quality appears to be correlated with lower WTP for improved electricity connections, lower probability of appliance damage, and lower value of protective devices owned (Table C11), but not with any outcomes not directly related to voltage. This may also explain why voltage improvements have limited impacts on outcomes not directly linked to voltage quality.

### 5.8 Cost–benefit analysis

MCC spent approximately \$14 million on low voltage line bifurcation in the Achimota, Dansoman, and Kaneshie districts of Accra, Ghana, which have an estimated combined population of around 49,000 households (GSS, 2014), or \$286 per household.

To get an estimate of the cost-benefit ratio, we first use stated willingness to pay (described in Subsection 4.4) as an estimate of value. For an investment that generates perfect voltage quality but does not reduce outages (similar to what we find), an upper bound for the value to consumers is respondent WTP for a connection with perfect voltage quality and half their current outages.[30] Customers report being willing to pay at most an additional \$1.64 per month for such an improvement, or \$19.7 per year. Assuming a new transformer generates 30 years of usage, and using an annual discount rate of $\delta = 0.95$, this yields aggregate benefits of \$280 per household, or \$13.7 million across the 49,000 households in the three districts. This is a simple back of the envelope calculation—it could be an underestimate (if respondents are credit constrained) or an overestimate (the investments did not generate perfect voltage quality or reduce outages)—but may approximate the upper bound of benefits. Even so, it falls slightly below the costs of the line bifurcation investment.

Alternatively, we can calculate the benefit in terms of avoided investment in voltage protective devices (\$6) and on annual repairs and replacements of broken appliances (\$10.2). Eliminating all protective devices and 100% of damage repair/replacement expenditures every year for 30 years (discounting at $\delta = 0.95$) for all 49,000 households yields benefits of \$7.4 million, far short of the investment cost.

In either case, the benefits are unlikely to exceed the costs of the investment.

## 6 Conclusion

Global energy policy in low- and middle-income countries has thus far placed limited focus on the role of voltage quality for economic activity, in part due to data limitations for measuring both the severity of voltage problems and the impact on households and businesses. This paper collects and analyzes novel, temporally and spatially high-frequency power quality measurements to present the first detailed analysis of the large-scale economic impacts of voltage quality.

In collaboration with engineers, we deploy customer-level GridWatch devices across Accra, Ghana to document that poor voltage quality is a pervasive problem. Grid electricity is of poor

[30] The survey did not ask about a connection where only voltage improved.

quality—more than 10% below the nominal level of 230V—approximately 20% of the time.

We complement these data with socioeconomic surveys with more than 2,000 businesses and households to document that these issues create real economic costs for customers in terms of appliance damages and interference with business operations. Households and businesses are willing to pay similar amounts for electricity connections with reduced outages and with improved voltage, and they assign such improvements a similar share of hypothetical public investment, indicating that electricity quality imposes similar costs on customers as electricity reliability.

Next, we use a difference-in-differences design to estimate the impact of an intervention that injected new transformers into the electricity grid to improve electricity quality, at a cost of $286 per household. The intervention increases average voltage by 5V—especially reducing the most severe voltage problem—and modestly reduced voltage-related damages and ownership of protective devices.

However, the investment had no impact on household and businesses outcomes such as electricity spending, appliance ownership, business profits, and household income. Several factors could explain this. First, while the 5V difference between control and treatment sites at endline was statistically significant, it may have been economically insufficient. Average voltage at control sites during endline was 225V; within 5V of nominal voltage of 230V. Improvements at lower voltage levels may have larger economic impacts. Second, while average voltage improved, voltage sags—including large and lengthy drops in voltage—remain common post-construction. Voltage spikes following outages furthermore were not addressed by the intervention. Customers therefore still face significant voltage problems that could interfere with economic activity. Third, benefits may operate through increased appliance adoption, which we do not observe: this may be because customers did not have sufficient time to observe voltage improvements and respond to them, or investment may have been suppressed following economic effects of the COVID-19 pandemic.

These results present novel evidence on the economic costs of voltage quality, while at the same time highlighting the difficulty of achieving meaningful voltage improvements through infrastructure construction. While a definitive evaluation of optimal investment is beyond the scope of this paper, we offer a framework with which to evaluate such investments. Resource-constrained governments will need to evaluate the economic benefits of voltage improvements against the high cost of these infrastructure investments.

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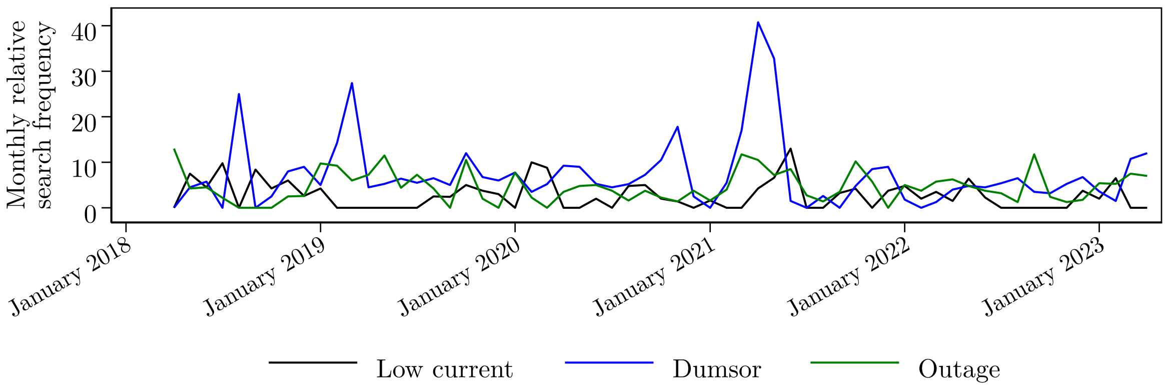
# A Appendix Figures

Figure A1: Google trends for search on voltage and outage issues in Ghana, April 2018-2023



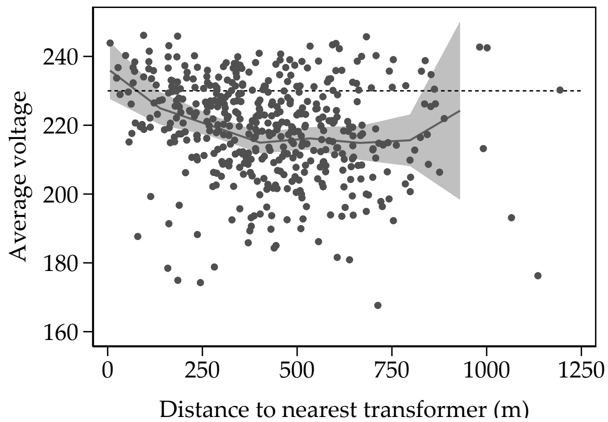

Data are aggregated from weekly Google Trends data for the specified search terms. Relative search frequency is calibrated to the maximum search interest across the three terms over the time period. “Low current” is the most common phrase used in Ghana to refer to issues related to voltage. “Dumsor”, meaning “off and on” in Akan, is a common term to refer to outages in Ghana, and is particularly associated with periods of load shedding and frequent long-lasting outages.

Figure A2: A GridWatch device


A GridWatch device, part of nLine’s GridWatch technologies used to measure power outages and voltage. Each GridWatch device measures voltage in real-time, stores this on a local SD card, and sends the data to the cloud via a sim card whenever local cellular service permits. A back-end computing technology aggregates these data in real-time, monitoring voltage at the device level and detecting spatial and temporal correlations in power loss and restoration signals to identify power outages with relatively high confidence.

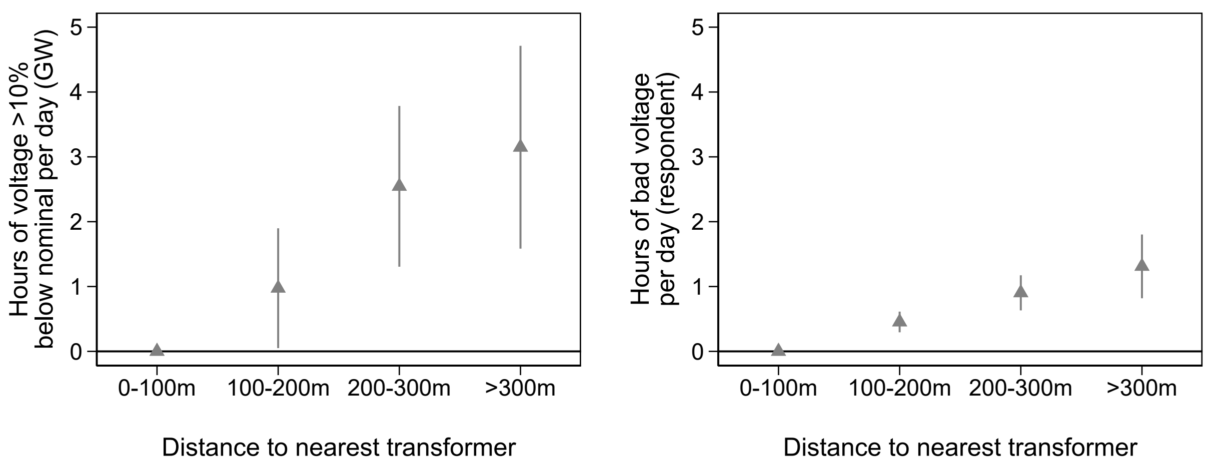
Figure A3: Correlation between average voltage and distance to nearest transformer

Panel (A) Raw correlation with GridWatch devices



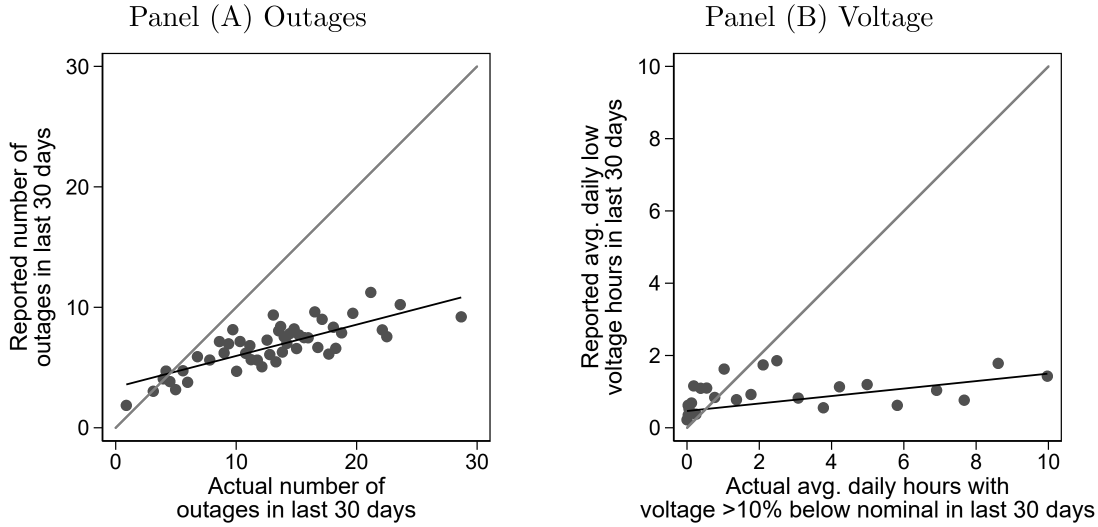

Panel (B) GridWatch devices

Panel (C) Self-reported



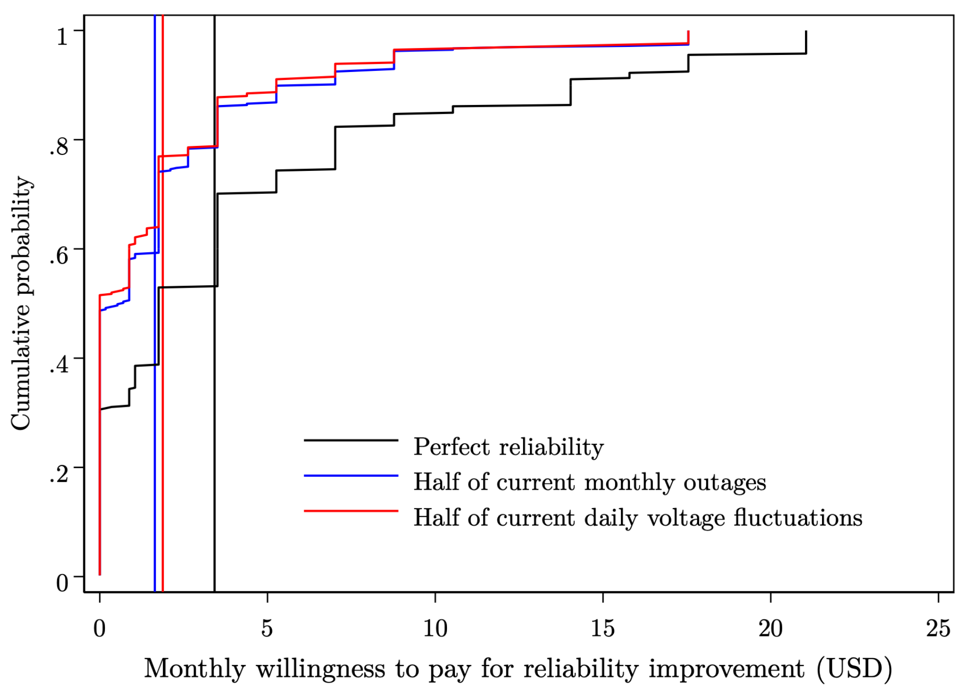

Panel A shows device-level average voltage by the distance along the electricity network from that device to the nearest transformer using GridWatch data from Ghana (described in Section 3). The black line shows the best fit from a local polynomial, and the shading show a 95% confidence band. For Panel B, respondents are matched with GridWatch data from the device that is nearest to their location (with 'bad' voltage being voltage more than 10% below nominal). For Panel C, respondents are asked about average daily 'bad' voltage hours and about the count of outages over the 30 days preceding the survey.

Figure A4: Correlations between measured and reported electricity characteristics



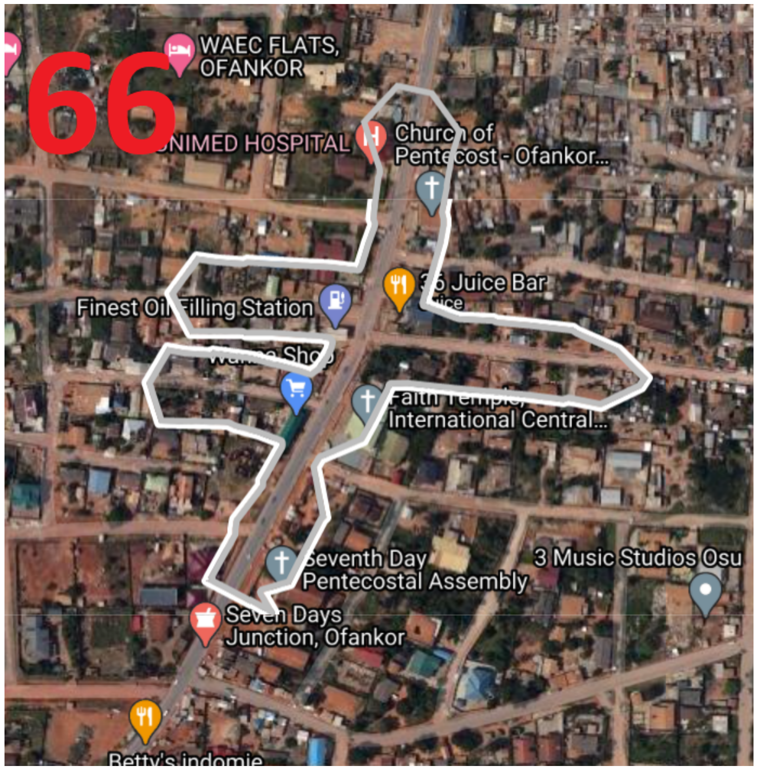

Respondents are asked about average daily 'bad' voltage hours and about the count of outages over the 30 days preceding the survey. Respondents are matched with GridWatch data from the device that is nearest to their location. Voltage more than 10% below nominal is used as a proxy for 'bad' voltage as defined by respondents.

Figure A5: Willingness to pay for electricity connections with particular characteristics



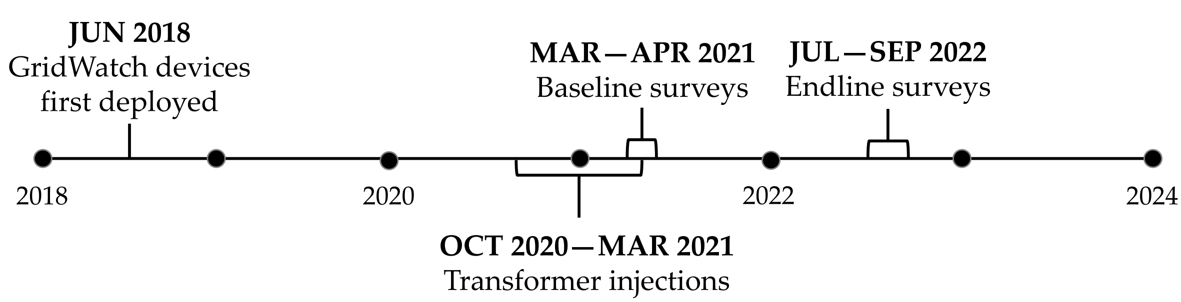

Willingness to pay is elicited first for connections with perfectly reliable electricity, and is then elicited for connections with specific reliability improvements. Vertical lines indicate the mean willingness to pay for each type of improved electricity connection. The mean monthly electricity spending for both businesses and households is USD 18.

Figure A6: Example of a surveyed site



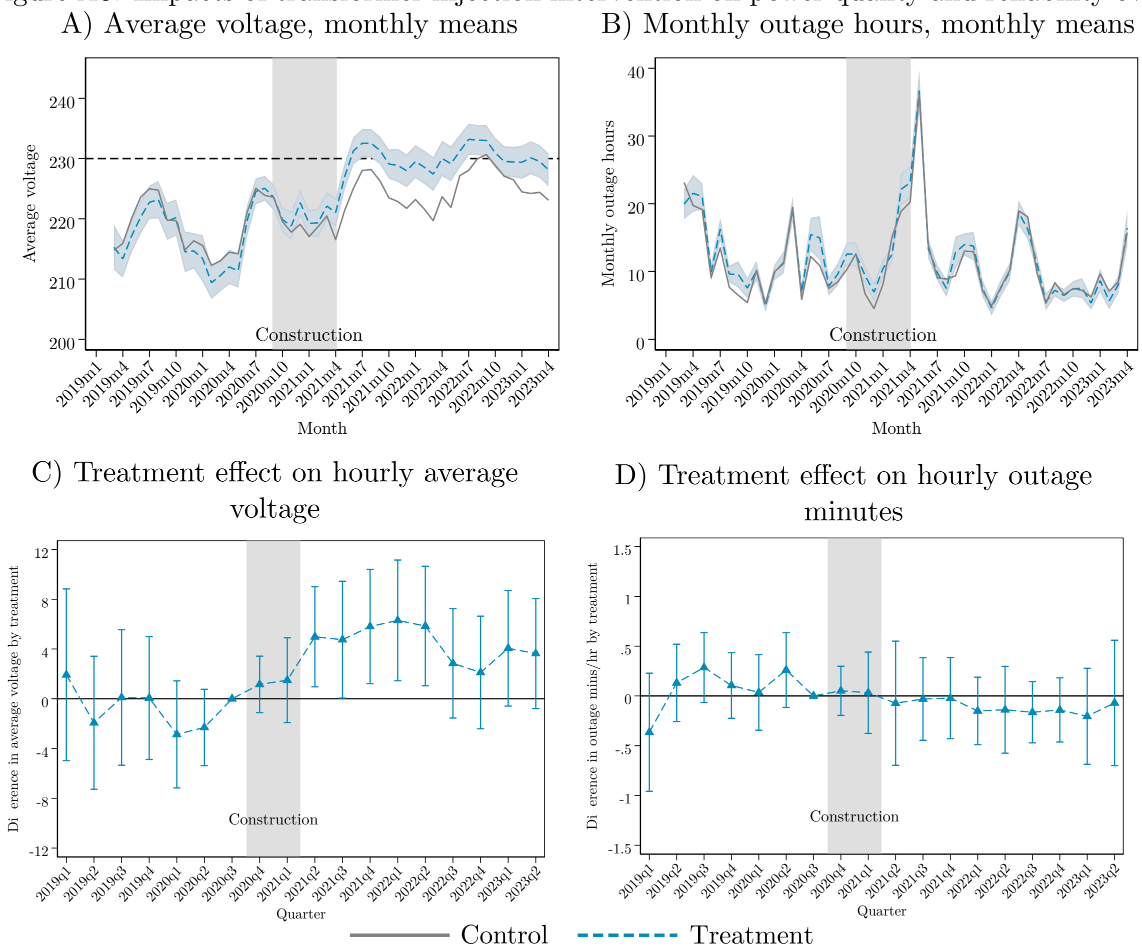

A sample site map where field officers conducted surveying. The outline in gray denotes the area within 200 meters of the proposed injection site and at least 300 meters from an existing transformer along the electricity network.

Figure A7: Project timeline



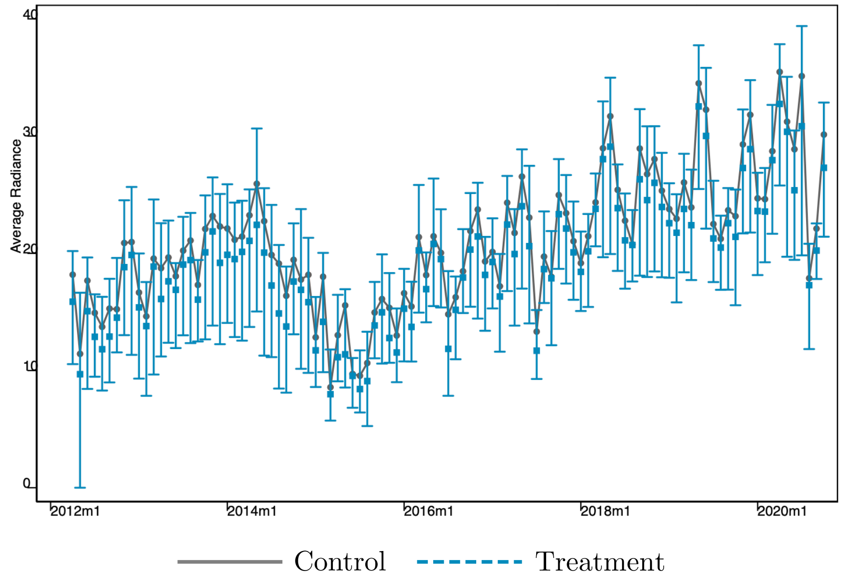

Timeline of research and construction activities. GridWatch data were collected continuously in the months after device deployment. The analyses in this paper include GridWatch data collected through April 2023.

Figure A8: Impacts of transformer injection intervention on power quality and reliability over time



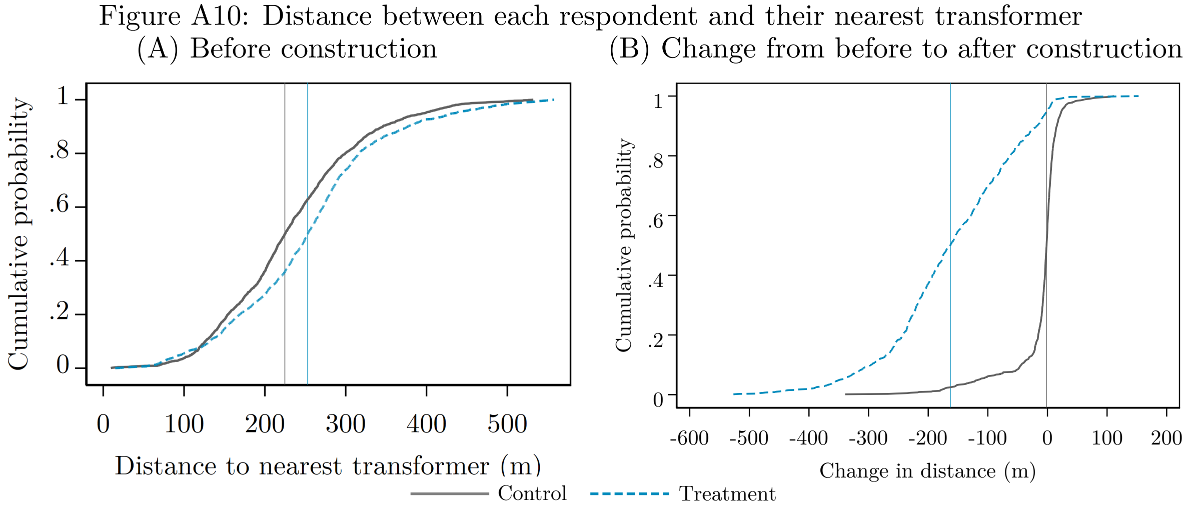

Panels A and B show monthly mean values by treatment. with 95% confidence intervals. Panels C and D show estimated coefficients and 95% confidence intervals from a regression of outcomes on site treatment status by quarter, controlling for hour of day, week of year, and site fixed effects. SEs clustered by site.

Figure A9: Balance in nightlight radiance



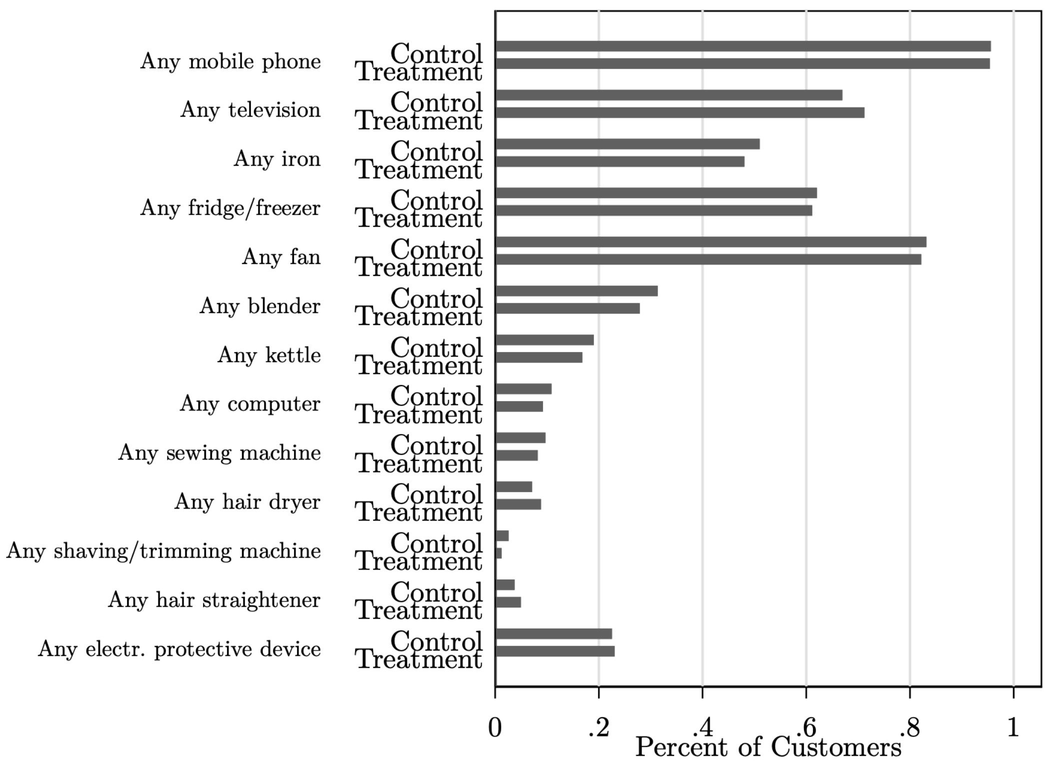

Median monthly nighttime radiance from VIIRS between 2012-2020 per site-month, with bands showing the 25th to 75th percentile.

Figure A10: Distance between each respondent and their nearest transformer




Panel A shows the distance (in meters) from each respondent to the nearest transformer at baseline to endline for survey respondents. Panel B shows the change in this distance from baseline to endline. Vertical lines mark the median respondents in control and treatment sites.

Figure A11: Appliance acquisition between surveys by site treatment status




Shares of business and household respondents reporting acquiring different types of appliances between baseline and endline, across treatment and control sites.

# B Appendix Tables

Table B1: Baseline balance by site status

| | Control N | Mean | Treat N | Diff. | $p$-value | Accra Mean |
|---|---|---|---|---|---|---|
| *Respondent and Location* | | | | | | |
| Age (years) | 772 | 38.79 | 803 | -0.85 | 0.141 | 45.39 |
| Respondent is male | 772 | 0.36 | 803 | 0.01 | 0.753 | 0.67 |
| Completed secondary education | 772 | 0.50 | 803 | -0.00 | 0.983 | |
| Owns premises | 772 | 0.37 | 803 | -0.02 | 0.368 | 0.59 |
| *Appliances* | | | | | | |
| Any television (TV) at location | 772 | 0.68 | 803 | -0.05 | 0.040 | 0.85 |
| Any fridge at location | 772 | 0.63 | 803 | 0.02 | 0.434 | 0.62 |
| Count of mobiles | 772 | 2.23 | 803 | 0.13 | 0.107 | 3.02 |
| Any voltage protective device | 772 | 0.24 | 803 | -0.02 | 0.411 | |
| Count of voltage defensive invest. | 772 | 0.35 | 803 | 0.01 | 0.694 | |
| *Electricity and Energy* | | | | | | |
| Pays someone else for electricity | 772 | 0.09 | 803 | 0.01 | 0.611 | |
| Count of meter users | 772 | 1.76 | 803 | -0.11 | 0.141 | |
| Monthly electricity spending | 763 | 19.37 | 796 | 1.96 | 0.026 | 5.99 |
| Has generator | 772 | 0.04 | 803 | 0.00 | 0.968 | 0.02 |
| Count of alternative fuels used in past 3 months | 772 | 0.92 | 803 | 0.00 | 0.919 | |
| Amount spent on all alt. fuels in past month | 772 | 8.73 | 803 | 1.40 | 0.241 | |
| *Electricity Reliability and Quality* | | | | | | |
| Reported number of outages in past month | 772 | 6.98 | 803 | 0.35 | 0.139 | |
| Total outage hours in past month | 772 | 38.61 | 803 | -1.47 | 0.541 | |
| Reported avg. hours per day with bad voltage | 769 | 1.44 | 797 | -0.29 | 0.062 | |
| Any appliance damaged by voltage in past year | 772 | 0.25 | 803 | -0.04 | 0.056 | |
| Amt. spent on burnt/broken apps in past year | 768 | 10.11 | 794 | -0.28 | 0.877 | |
| *Household Characteristics* | | | | | | |
| Adult members | 363 | 2.38 | 383 | -0.03 | 0.758 | 2.11 |
| Child members (<18) | 363 | 1.19 | 383 | -0.04 | 0.721 | 1.34 |
| Total household monthly income | 347 | 390.34 | 367 | -6.43 | 0.864 | 328.25 |
| Share of HH adults (18+) with paid jobs in last 7 days | 363 | 0.64 | 383 | -0.03 | 0.265 | |
| *Business Characteristics* | | | | | | |
| Number of workers | 409 | 1.99 | 420 | 0.04 | 0.790 | 7 |
| Total revenue in past month | 343 | 438.36 | 380 | -0.59 | 0.990 | 7187.5 |
| Total measured business costs in past month | 325 | 311.90 | 366 | -28.63 | 0.359 | |
| Total profit in past month | 310 | 112.81 | 336 | 9.01 | 0.457 | 1851.44 |
| Total hours typically open | 409 | 12.16 | 420 | 0.19 | 0.268 | |
| Any non-electric business machines at location | 409 | 0.09 | 420 | -0.00 | 0.905 | |
| Business engaged in retail activities | 409 | 0.44 | 420 | -0.00 | 0.933 | |
| Business engaged in manufacturing activities | 409 | 0.22 | 420 | 0.02 | 0.378 | |
| Business engaged in other service activities | 409 | 0.35 | 420 | -0.02 | 0.514 | |
| Business activity likely using electricity | 409 | 0.23 | 420 | 0.01 | 0.710 | |

Notes: This table shows means in the baseline period for survey respondents, pooling businesses and households, and tests for significance of the differences in means by line bifurcation treatment status. The p-value for the joint F-test for household baseline characteristics is 0.185. The p-value for the joint F-test for business baseline characteristics is 0.442. Summary statistics for the population of households in Accra are taken from Ghana Statistical Service data from the 2017 Ghana Living Standards Survey or the 2015 Labor Force Survey for urban households in the Greater Accra Region and calculated using survey weights to generate representative estimates. Summary statistics for the population of businesses in Accra are taken from Ghana Statistical Service data from the 2015 Integrated Business Establishment Survey II for businesses in urban Accra with 30 or fewer employees, which are sampled randomly from the 2013 census of Ghanaian businesses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B2: Does power quality affect political preferences?

| | (1) | (2) | (3) |
|---|---|---|---|
| Monthly bad voltage days | 0.000 | -0.000 | 0.001 |
| | (0.002) | (0.002) | (0.003) |
| Monthly outage days | 0.011 | 0.030 | 0.009 |
| | (0.025) | (0.028) | (0.092) |
| Observations | 1565 | 1565 | 1561 |
| Mean | 0.340 | 0.340 | 0.340 |
| Week FE | | Yes | Yes |
| Site FE | | | Yes |

Table B3: Testing voltage spillovers in control sites from transformer injection intervention

| | (1) | (2) |
|---|---|---|
| Post construction | 7.37*** | 6.53* |
| | (2.00) | (3.44) |
| Post construction × Below median distance to nearest injection site | -3.79<br>(2.90) | |
| Post construction × Distance to nearest injection site (100m) | | -0.06<br>(0.17) |
| Observations | 4936545 | 4936545 |
| Pre-construction mean, above median distance to injection | 220.1 | 220.1 |
| Hour of day FE | Y | Y |
| Week of year FE | Y | Y |
| Site FE | Y | Y |

This table tests for differences in how voltage changed in control sites—which did not receive any new transformers—after the transformer construction intervention by distance along the grid network from the control site to the nearest new injection transformer. Voltage is measured using hourly voltage data at the GridWatch device level. Column (1) tests for differences by whether a device is in a site below the median distance to the nearest injection transformer, while Column (2) tests for differences by distance, measured in 100m. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B4: Impact of transformer injection intervention on customer electricity experience

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post × Treat (SE) |
|---|---|---|---|---|---|
| Voltage damage and protection index | 3150 | 0.00 | -0.11** | 0.09 | -0.10* |
| | | (1.00) | (0.05) | (0.06) | (0.06) |
| Any appliance damaged by voltage in past year | 3150 | 0.25 | -0.05* | 0.04 | -0.05 |
| | | (0.43) | (0.03) | (0.03) | (0.04) |
| Any voltage protective devices | 3150 | 0.25 | -0.02** | 0.02 | -0.02 |
| | | (0.44) | (0.01) | (0.02) | (0.01) |
| Amt spent on burnt/broken apps in past year | 3080 | 10.22 | -6.90*** | 0.25 | 1.15 |
| | | (37.23) | (1.47) | (1.98) | (2.05) |
| Value of voltage protective devices | 2668 | 6.05 | -3.06*** | 0.52 | 0.22 |
| | | (25.51) | (1.00) | (1.57) | (1.70) |
| Reported hours of bad voltage in past month | 3130 | 43.05 | -42.36*** | 8.56 | -9.12 |
| | | (87.25) | (4.69) | (7.47) | (7.64) |
| Reported total outage hours in past month | 3092 | 32.20 | -29.33*** | 1.77 | -1.12 |
| | | (31.09) | (2.02) | (2.64) | (2.73) |
| Max monthly WTP for perfect reliability | 3150 | 3.62 | -1.84*** | -0.37 | 0.47 |
| | | (4.85) | (0.22) | (0.27) | (0.30) |
| Max monthly WTP for half of curr. outages | 3150 | 1.74 | -0.59*** | -0.18 | 0.22 |
| | | (2.98) | (0.17) | (0.19) | (0.22) |
| Max monthly WTP for half of curr. volt. fluc. | 2000 | 2.14 | -0.42 | -0.42 | 0.57 |
| | | (3.68) | (0.30) | (0.36) | (0.39) |
| Total number of appliances | 3150 | 8.59 | 0.04 | -0.10 | 0.08 |
| | | (5.98) | (0.09) | (0.34) | (0.13) |
| Uses an alternative energy source | 3150 | 0.05 | -0.01 | 0.00 | -0.00 |
| | | (0.22) | (0.01) | (0.01) | (0.01) |
| Monthly electricity spending | 3050 | 19.51 | -6.41*** | -2.01* | 0.77 |
| | | (18.67) | (0.67) | (1.12) | (0.89) |
| Total profit in past month | 1104 | 108.61 | -21.45** | -11.91 | 5.21 |
| | | (158.44) | (10.80) | (12.02) | (14.07) |
| Total revenue in past month | 1280 | 436.45 | 18.37 | 5.87 | -87.44 |
| | | (689.48) | (43.52) | (55.89) | (58.15) |
| Total monthly reported business spending | 1206 | 304.41 | 34.28 | 38.12 | -97.95** |
| | | (395.39) | (35.48) | (38.04) | (49.39) |
| Total household monthly income | 1358 | 360.69 | -76.42** | 12.66 | -72.63 |
| | | (491.13) | (36.60) | (43.51) | (50.21) |

Notes: This table shows the difference-in-difference results from the Equation 2 pooling businesses and households. Each row represents an outcome. All outcomes pre-specified in the pre-analysis plan (Berkouwer et al., 2019). All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Results are qualitatively unchanged when using logged versions of continuous outcomes. Sample sizes vary for some questions because of missing data, particularly when respondents were unable to estimate monetary values with a high degree of confidence, or because some questions were only asked to a subset of respondents. Reliability outcomes are measured using respondent self-reports based on the 30 days prior to the survey date at both baseline and endline. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is a household or a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sharpened FDR q-values following Anderson (2008) are shown in Table C8. All effects of Post remain statistically significant after this adjustment, but the significant effects of Post × Treat do not.

Table B5: Impact of transformer injection intervention on main business outcomes

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Total profit in past month | 1339 | 112.81 | -24.29** | -10.05 | -10.73 |
| | | [166.13] | (10.58) | (12.75) | (19.48) |
| Total monthly reported business spending | 1407 | 316.09 | 29.35 | 26.51 | -94.98* |
| | | [417.09] | (37.18) | (38.80) | (49.36) |
| Total wages and benefits paid in past month | 1483 | 63.89 | 8.55 | -3.40 | -9.25 |
| | | [159.07] | (9.49) | (11.53) | (12.43) |
| Total materials cost in past month | 1438 | 212.79 | 36.09 | 40.06 | -90.48** |
| | | [337.94] | (29.11) | (29.38) | (40.00) |
| Monthly electricity spending | 1625 | 19.36 | -6.34*** | -1.90 | 0.45 |
| | | [18.63] | (0.79) | (1.27) | (1.02) |
| Amount spent on all alt. fuels in past month | 1658 | 5.66 | -1.69 | -1.57 | 1.31 |
| | | [41.22] | (1.90) | (2.16) | (2.04) |
| Total revenue in past month | 1443 | 438.36 | 15.74 | -0.67 | -99.30* |
| | | [675.55] | (42.47) | (53.22) | (56.60) |
| Estimated change in revenue with perfect electricity | 1302 | 544.86 | -329.84*** | -102.81 | 9.04 |
| | | [1958.40] | (118.00) | (132.79) | (138.45) |
| Number of workers | 1658 | 1.99 | 0.11* | -0.02 | 0.07 |
| | | [1.90] | (0.06) | (0.13) | (0.09) |
| Share of men employees | 1652 | 0.31 | -0.01 | 0.00 | 0.00 |
| | | [0.42] | (0.01) | (0.01) | (0.02) |
| Share of full-time employees | 1643 | 0.91 | -0.05*** | 0.01 | -0.00 |
| | | [0.21] | (0.02) | (0.02) | (0.02) |
| Business open during any 'dark' hours | 1658 | 0.77 | -0.08*** | -0.01 | -0.02 |
| | | [0.42] | (0.03) | (0.03) | (0.04) |
| Total hours typically open | 1658 | 12.16 | -0.58*** | -0.13 | -0.16 |
| | | [2.46] | (0.13) | (0.19) | (0.22) |
| Applied for loans in past 12 months | 1658 | 0.17 | -0.01 | 0.04 | -0.01 |
| | | [0.38] | (0.03) | (0.03) | (0.04) |
| Total value of outstanding loans | 1626 | 360.60 | -26.12 | 83.53 | -160.55 |
| | | [1220.47] | (77.14) | (95.73) | (109.57) |

Notes: This table shows the difference-in-difference results from the main equation. Each row represents an outcome. All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is the business owner or a manager, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B6: Impact of transformer injection on household outcomes

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Total household monthly income | 1421 | 390.34 | -93.92* | 712.18 | -754.22 |
| | | [713.36] | (51.03) | (655.06) | (635.45) |
| Monthly rent | 561 | 33.89 | -8.65*** | 3.14 | -1.58 |
| | | [26.29] | (1.51) | (3.77) | (3.00) |
| Share of HH adults (18+) with paid jobs in last 7 days | 1488 | 0.64 | -0.02 | 0.04 | -0.05 |
| | | [0.36] | (0.03) | (0.03) | (0.04) |
| Household use of dirty cooking fuel (past 3 months) | 1492 | 0.65 | 0.08*** | -0.04 | 0.04 |
| | | [0.48] | (0.02) | (0.03) | (0.04) |
| Total spending on health in past 2 weeks | 1450 | 14.35 | 3.10 | -1.43 | 3.72 |
| | | [38.22] | (2.85) | (2.59) | (3.83) |
| Household qualitative assessments index | 1492 | 1.38 | -1.38*** | 0.02 | 0.03 |
| | | [2.26] | (0.16) | (0.21) | (0.23) |
| Perceived safety in area (1-5) | 1491 | 3.51 | 0.02 | -0.16* | 0.05 |
| | | [0.97] | (0.07) | (0.09) | (0.12) |
| Belief that Dumsor is back (1-5) | 1489 | 2.99 | 1.32*** | -0.01 | 0.06 |
| | | [1.27] | (0.10) | (0.12) | (0.13) |
| Expected reliability one year from today (1-3) | 1238 | 2.32 | 0.32*** | 0.05 | -0.01 |
| | | [0.79] | (0.07) | (0.08) | (0.09) |
| Loss of perishable food due to reliability (0-2) | 1489 | 0.34 | -0.31*** | -0.03 | 0.04 |
| | | [0.54] | (0.03) | (0.05) | (0.05) |
| Loss of perishable medicine due to reliability (0-2) | 1489 | 0.04 | -0.03*** | 0.00 | -0.00 |
| | | [0.20] | (0.01) | (0.02) | (0.02) |
| Household health challenges due to reliability issues | 1488 | -0.00 | -0.00 | 0.07 | -0.02 |
| | | [1.00] | (0.07) | (0.08) | (0.12) |
| Household study light quality index | 1492 | 0.00 | -0.04 | -0.07 | 0.03 |
| | | [1.00] | (0.06) | (0.06) | (0.07) |
| Hours per day lightbulbs used for reading or studying | 713 | 0.91 | 0.07*** | 0.01 | -0.02 |
| | | [0.23] | (0.02) | (0.02) | (0.03) |
| Share of hours per day readng or studying with lightbulbs vs other light sources | 1492 | 0.13 | -0.09*** | -0.04 | 0.03 |
| | | [0.59] | (0.03) | (0.04) | (0.04) |

Notes: This table shows the difference-in-difference results from the main equation. Each row represents an outcome. Total household monthly income reflects the sum of incomes from any source for all household members of age 16 and above. Monthly rent is missing for individuals who do not rent or occupy the premises rent free. Dirty cooking fuel includes wood, charcoal, and animal waste, but not gas, electricity, or kerosene. All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Logs of continuous variables are taken after adding 1 to the value to deal with 0 values; results are unchanged when using inverse hyperbolic sine. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, the count of all household members and of household adults, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B7: Heterogeneous impacts of transformer injection intervention on primary outcomes

| | Avg. voltage (below median) | Elec. imp. (high) | WTP reliab. (above median) | Defensive invst. (high) |
|---|---|---|---|---|
| Reported hours of bad voltage in past month | -12.63 | -2.16 | 4.55 | -6.69 |
| | (14.13) | (10.30) | (11.17) | (12.78) |
| Reported total outage hours in past month | -3.62 | -0.16 | -0.31 | -7.79 |
| | (7.07) | (4.78) | (5.61) | (5.48) |
| Max monthly WTP for perfect reliability | 0.93 | 0.17 | 0.92** | 0.13 |
| | (0.58) | (0.49) | (0.44) | (0.59) |
| Max monthly WTP for half of curr. outages | 0.79* | 0.32 | 0.40 | 0.07 |
| | (0.42) | (0.33) | (0.35) | (0.45) |
| Max monthly WTP for half of curr. volt. fluc. | 1.09 | 0.47 | 0.71 | -0.12 |
| | (0.77) | (0.70) | (0.70) | (0.97) |
| Voltage damage and protection index | 0.09 | 0.02 | -0.07 | -0.09 |
| | (0.11) | (0.11) | (0.10) | (0.13) |
| Any appliance damaged by voltage in past year | 0.03 | -0.00 | -0.00 | -0.05 |
| | (0.07) | (0.06) | (0.06) | (0.08) |
| Amt spent on burnt/broken apps in past year | -1.81 | 0.17 | -4.62 | 0.49 |
| | (3.95) | (4.31) | (4.04) | (5.52) |
| Any voltage protective devices | 0.03 | 0.02 | -0.05* | -0.01 |
| | (0.02) | (0.02) | (0.03) | (0.04) |
| Value of voltage protective devices | -6.75 | 3.16 | -9.01 | -6.97 |
| | (7.52) | (6.59) | (8.96) | (20.61) |
| Uses an alternative energy source | 0.00 | 0.03* | -0.03 | -0.01 |
| | (0.02) | (0.02) | (0.02) | (0.02) |
| Total number of appliances | 0.09 | 0.12 | -0.32 | 0.01 |
| | (0.25) | (0.28) | (0.26) | (0.36) |
| Monthly electricity spending | -2.13 | -0.99 | -0.14 | -0.18 |
| | (1.76) | (1.50) | (1.74) | (2.05) |
| Total profit in past month | 10.69 | -29.93 | -8.64 | -6.65 |
| | (38.08) | (33.57) | (34.16) | (36.05) |
| Total revenue in past month | 186.31* | 257.11* | 30.43 | -136.39 |
| | (110.41) | (144.42) | (111.26) | (124.52) |
| Total monthly reported business spending | 111.06 | 227.17** | 12.94 | -40.33 |
| | (97.86) | (110.73) | (89.19) | (104.95) |
| Total household monthly income | 36.10 | 0.00 | -55.06 | 37.39 |
| | (96.70) | (.) | (84.47) | (98.06) |

Notes: This table shows the heterogeneous treatment estimates by (1) baseline average dailxy hours with good voltage (2) electricity importance at baseline (3) baseline WTP for perfect reliability and (4) baseline count of voltage defensive investment. In column (1), "below median" is a dummy variable for those that are below the median in terms of average number of hours of good voltage quality at baseline. In column (2), a firm is classified as "high importance" if the owner reported that electricity is "very important" or "extremely important" when they were asked about the importance of electricity as an obstacle at baseline. In column (3), a firm is classified as "high WTP" if their WTP for perfect reliability is greater than or equal to the 50th percentile. In column (4), "High" refers to firms that report having at least 1 defensive investment at baseline. We estimate a coefficient for each of the four groups, using the following equation: $Y_{it}$=$\alpha_0$ + $\alpha_1$ $Group * Treat * Post_{it}$ + $\alpha_2$ $Group * Treat_{it}$ + $\alpha_3$ $Group * Post_{it}$ + $\alpha_4$ $Post * Treat_{it}$+ $\alpha_5$ $Post_t$ + $\alpha_6$ $Treat_i$ + $\alpha_7$ $Group_i$ +$u_{it}$; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

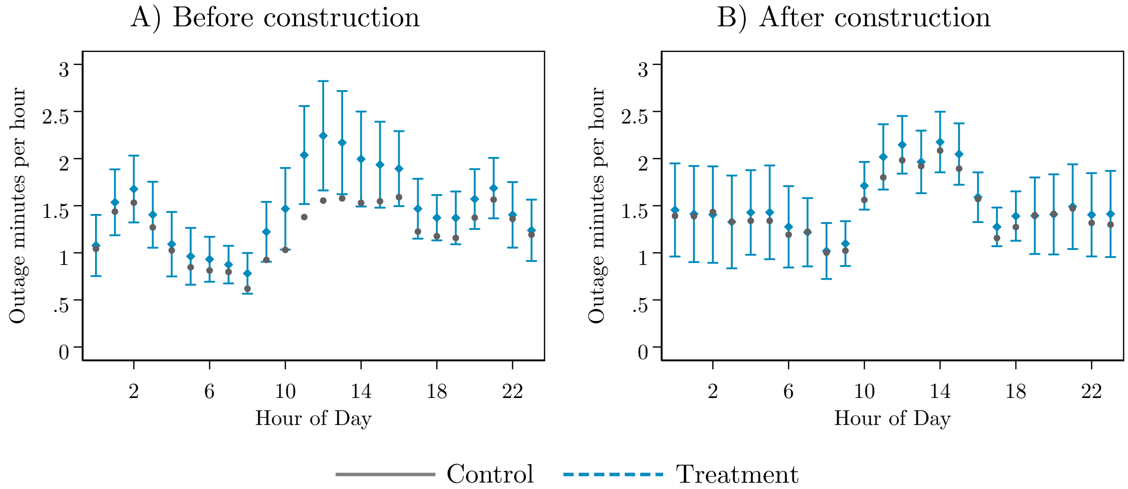
Table B8: Impacts of transformer injection intervention on voltage by baseline voltage quality

| | (1) All sites | (2) Below median baseline voltage | (3) Above median baseline voltage | (4) All sites |
|---|---|---|---|---|
| Post construction | 5.94*** | 10.02*** | 1.85 | |
| | (1.74) | (2.99) | (1.32) | |
| During construction | 0.76 | 2.04 | -0.01 | |
| | (1.09) | (2.15) | (1.07) | |
| Treat × Post | 5.48** | 8.70** | 2.20 | |
| | (2.48) | (4.09) | (2.00) | |
| Treat × During | 2.38 | 5.65* | -0.99 | |
| | (1.60) | (2.84) | (1.48) | |
| Below median baseline voltage | | | | 0.00 |
| | | | | (.) |
| Post construction=1 × Below median baseline voltage | | | | 7.92** |
| | | | | (3.23) |
| During construction=1 × Below median baseline voltage | | | | 1.44 |
| | | | | (2.29) |
| Treat × Post × Below median baseline voltage | | | | 6.46 |
| | | | | (4.54) |
| Treat × During× Below median baseline voltage | | | | 6.61** |
| | | | | (3.19) |
| Observations | 9866078 | 5258541 | 4607537 | 9866078 |
| Pre-construction control mean | 219.18 | 210.02 | 227.71 | 227.71 |
| Hour of day FE | Y | Y | Y | Y |
| Week of year FE | Y | Y | Y | Y |
| Site FE | Y | Y | Y | Y |

Notes: This table shows the difference-in-differences estimates by baseline voltage quality, measured as the mean share of the time in each site that voltage was within 10% of nominal. Subsetting by baseline voltage is done separately for treatment and control sites, so the samples always include an equal number of each. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

# C Appendix: Robustness checks

Figure C1: Impacts of transformer injection on outages by time of day




The figure shows mean minutes of power outages by hour of day separately for treatment and control sites. 95% confidence intervals around treatment means are clustered at the site level. Panel A shows means for the year prior to the start of the transformer construction period, and Panel B shows means for the year after the end of the construction period. Figure 4 shows impacts on average voltage.

Table C1: Correlation between attrited respondents' characteristics and treatment status

| | Mean | LB Treat | N |
|---|---|---|---|
| Age (years) | 37.11 | -1.20 | 426 |
| | [12.40] | (1.09) | |
| Respondent is male | 0.37 | -0.07 | 426 |
| | [0.48] | (0.05) | |
| Completed secondary education | 0.54 | 0.04 | 426 |
| | [0.50] | (0.05) | |
| Owns premises | 0.31 | -0.12*** | 426 |
| | [0.47] | (0.04) | |
| Any television (TV) at location | 0.69 | 0.08* | 426 |
| | [0.47] | (0.04) | |
| Any fridge at location | 0.60 | 0.02 | 426 |
| | [0.49] | (0.05) | |
| Count of mobile phones | 2.22 | -0.20 | 426 |
| | [2.00] | (0.18) | |
| Any voltage protective devices | 0.26 | -0.03 | 426 |
| | [0.44] | (0.04) | |
| Count of voltage defensive invest. | 0.35 | -0.03 | 426 |
| | [0.68] | (0.07) | |
| Amt spent on burnt/broken apps in past year | 5.06 | 1.31 | 426 |
| | [21.41] | (2.23) | |
| Pays someone else for electricity | 0.17 | -0.00 | 426 |
| | [0.38] | (0.04) | |
| Count of meter users | 2.18 | 0.02 | 424 |
| | [2.25] | (0.20) | |
| Monthly electricity spending | 18.86 | -1.94 | 413 |
| | [18.27] | (1.81) | |
| Has generator | 0.02 | 0.01 | 426 |
| | [0.14] | (0.02) | |
| Count of alternative fuels used in past 3 months | 0.96 | 0.05 | 426 |
| | [0.82] | (0.08) | |
| Amount spent on all alt. fuels in past month | 7.00 | 3.12 | 426 |
| | [9.25] | (2.09) | |
| Average number of monthly outages - resp. | 6.76 | -0.43 | 426 |
| | [4.82] | (0.44) | |
| Total outage duration in past 30 days (hrs) | 36.26 | 1.18 | 426 |
| | [47.33] | (4.43) | |
| Average daily hrs with low voltage - resp. | 1.42 | 0.03 | 422 |
| | [3.41] | (0.31) | |
| Has apps. burnt/broken due to voltage in past year | 0.24 | -0.01 | 426 |
| | [0.43] | (0.04) | |

Notes: This table shows the correlation between the attrited respondents' characteristics and treatment status. The sample is restricted to respondents who do not participate in the endline survey. We regress each respondent characteristic at baseline on a dummy variable equals one if the respondent was in a treatment site at baseline. Each row represents an outcome. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C2: Balance between panel and attrited respondents

| | Matched N | Mean | Attrited N | Difference | p-value |
|---|---|---|---|---|---|
| *Respondent and Location* | | | | | |
| Age (years) | 1575 | 39.23 | 426 | 2.73 | 0.000 |
| Respondent is male | 1575 | 0.35 | 426 | 0.02 | 0.547 |
| Completed secondary education | 1575 | 0.50 | 426 | -0.05 | 0.050 |
| Owns premises | 1575 | 0.38 | 426 | 0.12 | 0.000 |
| *Appliances* | | | | | |
| Any television (TV) at location | 1575 | 0.71 | 426 | -0.02 | 0.419 |
| Any fridge at location | 1575 | 0.62 | 426 | 0.01 | 0.835 |
| Count of mobile phones | 1575 | 2.17 | 426 | 0.05 | 0.605 |
| Any voltage protective devices | 1575 | 0.25 | 426 | 0.01 | 0.571 |
| Count of voltage defensive invest. | 1575 | 0.34 | 426 | 0.00 | 0.978 |
| *Electricity and Energy* | | | | | |
| Pays someone else for electricity | 1575 | 0.09 | 426 | -0.08 | 0.000 |
| Count of meter users | 1566 | 1.82 | 424 | -0.38 | 0.001 |
| Monthly electricity spending | 1559 | 18.37 | 413 | 0.50 | 0.615 |
| Has generator | 1575 | 0.04 | 426 | 0.02 | 0.070 |
| Count of alternative fuels used in past 3 months | 1575 | 0.91 | 426 | -0.07 | 0.107 |
| Amount spent on all alt. fuels in past month | 1575 | 8.62 | 426 | 0.01 | 0.993 |
| *Electricity Reliability and Quality* | | | | | |
| Average number of monthly outages - resp. | 1575 | 6.81 | 426 | 0.26 | 0.295 |
| Total outage duration in past 30 days (hrs) | 1575 | 42.05 | 426 | 5.19 | 0.059 |
| Average daily hrs with low voltage - resp. | 1566 | 1.58 | 422 | 0.14 | 0.408 |
| Has apps. burnt/broken due to voltage in past year | 1575 | 0.27 | 426 | 0.03 | 0.141 |
| Amt spent on burnt/broken apps in past year | 1562 | 10.25 | 426 | 4.52 | 0.002 |
| *Household Characteristics* | | | | | |
| Adult members | 746 | 2.39 | 251 | 0.28 | 0.001 |
| Child members (<18) | 746 | 1.21 | 251 | 0.24 | 0.014 |
| Total household monthly income | 714 | 729.62 | 234 | 252.66 | 0.444 |
| Share of HH adults (18+) with paid jobs in last 7 days | 746 | 0.66 | 251 | -0.04 | 0.123 |
| *Business Characteristics* | | | | | |
| Number of workers | 829 | 1.97 | 175 | -0.11 | 0.579 |
| Total revenue in past month | 723 | 438.67 | 147 | -72.32 | 0.292 |
| Total measured business costs in past month | 1575 | 173.44 | 426 | 14.96 | 0.390 |
| Total profit in past month | 646 | 108.12 | 131 | -34.17 | 0.063 |
| Total hours typically open | 829 | 12.07 | 175 | 0.20 | 0.397 |
| Any non-electric business machines at location | 829 | 0.09 | 175 | 0.00 | 0.992 |
| Business engaged in retail activities | 829 | 0.44 | 175 | -0.07 | 0.085 |
| Business engaged in manufacturing activities | 829 | 0.20 | 175 | 0.11 | 0.000 |
| Business engaged in other service activities | 829 | 0.36 | 175 | -0.03 | 0.409 |
| Business activity likely using electricity | 829 | 0.22 | 175 | 0.09 | 0.004 |

Notes: This table shows means in the baseline period for survey respondents, pooling businesses and households, and tests for significance of the differences in means by whether the respondent was also surveyed at the endline. The p-value for the joint F-test for household baseline characteristics is 0.001. The p-value for the joint F-test for business baseline characteristics is 0.028. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C3: Impact of transformer injection intervention on hourly average voltage, robustness to implementation issues

| | (1) All sites | (2) Commissioned sites (SMEC) | (3) New tx confirmed sites | (4) All sites, IV new tx with treat | (5) All sites |
|---|---|---|---|---|---|
| During construction | 0.76 | 0.79 | 0.65 | 0.42 | 0.79 |
| | (1.09) | (1.09) | (1.18) | (1.22) | (1.55) |
| Treat X During | 2.38 | 2.55 | 3.61** | | 1.95 |
| | (1.60) | (1.63) | (1.70) | | (1.93) |
| New Trafo X During | | | | 3.24 | |
| | | | | (2.05) | |
| Post construction | 5.94*** | 5.95*** | 5.26*** | 5.26*** | 5.95*** |
| | (1.74) | (1.75) | (1.85) | (1.95) | (1.82) |
| Treat X Post | 5.48** | 6.07** | 8.413*** | | 5.456** |
| | (2.48) | (2.49) | (2.48) | | (2.59) |
| New Trafo X Post | | | | 7.13** | |
| | | | | (3.13) | |
| Observations | 9866078 | 9723260 | 8815828 | 9866078 | 9866078 |
| Pre-constr. ctl. mean | 219.2 | 219.2 | 220.2 | 219.2 | 218.0 |
| Hour of day FE | Y | Y | Y | Y | Y |
| Week of year FE | Y | Y | Y | Y | Y |
| Site FE | Y | Y | Y | Y | Y |
| Revised constr. period | N | N | N | N | Y |

This table shows the difference-in-difference results for the impact of the transformer injection treatment on hourly average voltage levels measured by GridWatch devices in each site. Column 2 drops two sites where the construction manager SMEC indicated the new transformer was not commissioned successfully. Column 3 drops sites where our own construction monitoring activities indicated no new transformer was built in a treatment site or a new transformer was built in a control site. Column 4 instruments for observing a new transformer during the construction monitoring visits with site treatment assignment. Column 5 defines the construction period as July 1, 2020-December 31, 2020 instead of October 1, 2020-March 31, 2021, based on reported dates of transformer construction activity from the construction manager, SMEC. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C4: Impact of transformer injection intervention on hourly outage minutes, robustness to implementation issues

| | (1) All sites | (2) Commissioned sites (SMEC) | (3) New tx confirmed sites | (4) All sites, IV new tx with treat | (5) All sites |
|---|---|---|---|---|---|
| During construction | 0.21*** | 0.21*** | 0.16** | 0.22*** | 0.00 |
| | (0.071 | (0.07) | (0.08) | (0.08) | (0.08) |
| Treat X During | -0.06 | -0.07 | -0.04 | | -0.11 |
| | (0.12) | (0.12) | (0.13) | | (0.12) |
| New Trafo X During | | | | -0.09 | |
| | | | | (0.15) | |
| Post construction | -0.08 | -0.08 | -0.12 | -0.05 | -0.04 |
| | (0.08) | (0.08) | (0.08) | (0.09) | (0.08) |
| Treat X Post | -0.21 | -0.23* | -0.23 | | -0.23* |
| | (0.13) | (0.13) | (0.14) | | (0.14) |
| New Trafo X Post | | | | -0.28 | |
| | | | | (0.17) | |
| Observations | 10033086 | 9888612 | 8962703 | 10033086 | 10033086 |
| Pre-constr. ctl. mean | 1.39 | 1.39 | 1.41 | 1.39 | 1.48 |
| Hour of day FE | Y | Y | Y | Y | Y |
| Week of year FE | Y | Y | Y | Y | Y |
| Site FE | Y | Y | Y | Y | Y |
| Revised constr. period | | N | N | N | Y |

This table shows the difference-in-difference results for the impact of the transformer injection treatment on hourly power outage minutes measured by GridWatch devices in each site. Column 2 drops two sites where the construction manager SMEC indicated the new transformer was not commissioned successfully. Column 3 drops sites where our own construction monitoring activities indicated no new transformer was built in a treatment site or a new transformer was built in a control site. Column 4 instruments for observing a new transformer during the construction monitoring visits with site treatment assignment. Column 5 defines the construction period as July 1, 2020-December 31, 2020 instead of October 1, 2020-March 31, 2021, based on reported dates of transformer construction activity from the construction manager, SMEC. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C5: Impacts of transformer injection intervention on additional voltage quality measures, hourly data

| | N | Control Mean (SD) | During Construction (SE) | Post (SE) | Treat × During (SE) | Treat × Post (SE) |
|---|---|---|---|---|---|---|
| Mean voltage during hour | 9866078 | 219.18 | 0.76 | 5.94*** | 2.38 | 5.48** |
| | | (22.39) | (1.09) | (1.74) | (1.60) | (2.48) |
| Any voltage >20% below nominal | 10033086 | 0.08 | -0.00 | -0.03** | -0.03** | -0.04** |
| | | (0.26) | (0.01) | (0.01) | (0.02) | (0.02) |
| Minutes voltage >20% above nominal | 10033086 | 0.00 | -0.00 | -0.00 | -0.01 | -0.00 |
| | | (0.31) | (0.00) | (0.00) | (0.01) | (0.01) |
| Minutes voltage 10-20% below nominal | 10033086 | 9.60 | -0.59 | -2.96*** | -2.08* | -4.21*** |
| | | (19.83) | (0.61) | (0.93) | (1.15) | (1.41) |
| Minutes voltage >20% below nominal | 10033086 | 2.76 | 0.04 | -1.54*** | -1.39* | -1.40* |
| | | (11.59) | (0.56) | (0.57) | (0.77) | (0.85) |
| Minutes with no power (outage) | 10033086 | 1.39 | 0.21*** | -0.08 | -0.06 | -0.21 |
| | | (8.59) | (0.07) | (0.08) | (0.12) | (0.13) |

Notes: This table shows the difference-in-differences effects of the transformer injection intervention on measures of voltage quality using hourly data at the GridWatch device level. The minutes variables indicate the number of minutes in each hourly observation that the electricity had a certain status. 'Any voltage >20% below nominal' is a dummy variable for whether voltage fell below this threshold at any point during an hourly observation. All regressions include hour of day, week of year, and site fixed effects. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C6: Impacts of transformer injection intervention on additional voltage quality measures, monthly data

| | N | Control Mean (SD) | During Construction (SE) | Post (SE) | Treat × During (SE) | Treat × Post (SE) |
|---|---|---|---|---|---|---|
| Hours with no power (outages) | 19079 | 11.15 | 2.78*** | 1.12* | -0.04 | -1.34 |
| | | (10.96) | (0.59) | (0.65) | (0.92) | (1.09) |
| Number of spells with voltage <207 | 19079 | 185.36 | -2.58 | -31.75* | -13.83 | -45.75** |
| | | (265.45) | (12.77) | (16.29) | (18.90) | (23.26) |
| Number of spells with min voltage >200 | 19079 | 156.14 | -4.24 | -29.05** | -10.34 | -33.66* |
| | | (225.77) | (10.74) | (13.54) | (15.45) | (19.49) |
| Number of spells with min voltage btwn 184-200 | 19079 | 22.15 | 0.20 | -2.30 | -1.74 | -8.59** |
| | | (39.60) | (1.87) | (2.80) | (2.96) | (3.70) |
| Number of spells with min voltage <184 | 19079 | 7.07 | 1.46** | -0.40 | -1.75 | -3.50*** |
| | | (12.78) | (0.71) | (0.83) | (1.35) | (1.27) |
| Total hours of spells with voltage <207 | 19079 | 91.87 | 7.27 | -22.57** | -21.63 | -37.22** |
| | | (157.81) | (8.77) | (11.11) | (13.52) | (15.40) |
| Total hours of spells with min voltage >200 | 19079 | 11.68 | 0.64 | -1.42 | -0.17 | -2.72* |
| | | (16.83) | (0.85) | (1.05) | (1.18) | (1.47) |
| Total hours of spells with min voltage btwn 184-200 | 19079 | 24.08 | 1.59 | -3.36 | -0.55 | -5.88* |
| | | (39.92) | (2.04) | (2.44) | (2.86) | (3.22) |
| Total hours of spells with min voltage <184 | 19079 | 56.12 | 5.05 | -17.79** | -20.92* | -28.62** |
| | | (131.51) | (7.42) | (8.70) | (11.45) | (12.26) |
| Share of low-voltage time in spells with min voltage <184 | 14776 | 0.37 | -0.02 | 0.03 | -0.11*** | 0.01 |
| | | (0.38) | (0.02) | (0.02) | (0.04) | (0.04) |
| Mean spell length (hours) | 14776 | 0.75 | -0.10 | -0.31** | -0.04 | -0.08 |
| | | (2.14) | (0.12) | (0.14) | (0.16) | (0.19) |
| Median spell length (hours) | 14776 | 0.15 | -0.05 | -0.07** | 0.01 | 0.05 |
| | | (0.69) | (0.04) | (0.03) | (0.05) | (0.05) |
| Maximum spell length (hours) | 14776 | 10.92 | -0.79 | -2.95** | -2.86 | -4.46** |
| | | (20.49) | (1.27) | (1.48) | (1.75) | (2.15) |
| Mean of mean voltage during a spell | 14776 | 189.73 | 1.35 | -8.82*** | 1.18 | -14.22*** |
| | | (35.25) | (2.28) | (2.34) | (2.84) | (3.85) |
| Median of mean voltage during a spell | 14776 | 191.86 | 1.65 | -8.39*** | 1.89 | -14.22*** |
| | | (36.15) | (2.32) | (2.37) | (2.86) | (3.86) |
| Mean of minimum voltage during a spell | 14776 | 187.18 | 1.23 | -8.86*** | 2.22 | -13.70*** |
| | | (36.73) | (2.31) | (2.46) | (2.97) | (4.05) |

Notes: This table shows the difference-in-differences effects of the transformer injection intervention on measures of voltage quality using monthly data at the GridWatch device level. Outcomes in the first 4 rows measure the total hours in each monthly observation that the electricity had a certain status. Outcomes in all other rows are measured based on identifying individual low-voltage 'spells' during which voltage fell below 207V (10% below nominal) in any 2-minute interval. Individual spells with different characteristics are then aggregated to the month-device level. Months where there were no low voltage spells for particular devices are assigned a 0 for outcomes that are not conditional on experiencing at least one such spell. Number of spells refers to the number of individual low voltage spells in a device-month. Total hours of spells take the sum of the duration of individual spells in a device-month. Mean, median, and maximum spell length are statistics calculated over all individual spells in a device-month. Mean and median of mean spell voltage are statistics calculated over the mean voltage level within a spell for all individual spells in a device-month. Mean minimum voltage is calculated similarly. These statistics are conditional on any low-voltage spell being observed in a device-month. All regressions include month and site fixed effects. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C7: Impact of transformer injection intervention on primary outcomes for businesses

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Reported hours of bad voltage in past month | 1647 | 40.36 | -39.61*** | 9.54 | -10.26 |
| | | [82.33] | (4.33) | (8.08) | (8.27) |
| Reported total outage hours in past month | 1651 | 37.48 | -34.27*** | 1.21 | -0.35 |
| | | [45.04] | (3.33) | (4.49) | (4.59) |
| Max monthly WTP for perfect reliability | 1658 | 3.41 | -1.49*** | -0.30 | 0.36 |
| | | [4.79] | (0.27) | (0.33) | (0.37) |
| Max monthly WTP for half of curr. outages | 1658 | 1.74 | -0.49** | -0.29 | 0.36 |
| | | [3.07] | (0.19) | (0.21) | (0.26) |
| Max monthly WTP for half of curr. volt. fluc. | 1049 | 2.07 | -0.19 | -0.45 | 0.56 |
| | | [3.81] | (0.37) | (0.46) | (0.47) |
| Voltage damage and protection index | 1658 | -0.15 | -0.07 | 0.14 | -0.08 |
| | | [0.93] | (0.06) | (0.08) | (0.08) |
| Any appliance damaged by voltage in past year | 1658 | 0.22 | -0.01 | 0.04 | -0.05 |
| | | [0.41] | (0.03) | (0.04) | (0.04) |
| Amt spent on burnt/broken apps in past year | 1628 | 7.91 | -4.74*** | 0.13 | 1.56 |
| | | [30.66] | (1.75) | (2.31) | (2.38) |
| Any voltage protective device | 1658 | 0.19 | -0.03*** | 0.04 | -0.01 |
| | | [0.39] | (0.01) | (0.03) | (0.02) |
| Value of voltage protective devices | 1426 | 5.66 | -3.78** | -0.22 | -0.18 |
| | | [30.79] | (1.70) | (2.53) | (2.44) |
| Uses an alternative energy source | 1658 | 0.06 | -0.01 | -0.00 | 0.00 |
| | | [0.24] | (0.01) | (0.02) | (0.01) |
| Total number of appliances | 1658 | 7.07 | -0.08 | -0.02 | 0.18 |
| | | [5.54] | (0.13) | (0.36) | (0.19) |
| Monthly electricity spending | 1594 | 19.42 | -6.41*** | -1.74 | 0.42 |
| | | [18.71] | (0.81) | (1.30) | (1.05) |
| Total profit in past month | 1104 | 108.61 | -21.45** | -11.91 | 5.21 |
| | | [158.44] | (10.80) | (12.02) | (14.07) |
| Total revenue in past month | 1280 | 436.45 | 18.37 | 5.87 | -87.44 |
| | | [689.48] | (43.52) | (55.89) | (58.15) |
| Total monthly reported business spending | 1206 | 304.41 | 34.28 | 38.12 | -97.95** |
| | | [395.39] | (35.48) | (38.04) | (49.39) |

Notes: This table shows the difference-in-difference results from the Equation 2 for businesses only. Each row represents an outcome. All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Results are qualitatively unchanged when using logged versions of the outcomes. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is part of the household or business sample, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Refer to Table D5 for impacts of transformer injection on additional business outcomes.

Table C8: Impact of transformer injection intervention on primary outcomes

| | N | Control Mean (SD) | Post (SE) | FDR q-value | Treat (SE) | FDR q-value | Post × Treat (SE) | FDR q-value |
|---|---|---|---|---|---|---|---|---|
| Reported hours of bad voltage in past month | 3130 | 43.05 | -42.36*** | 0.001 | 8.56 | 0.622 | -9.12 | 0.444 |
| | | (87.25) | (4.69) | | (7.47) | | (7.64) | |
| Reported total outage hours in past month | 3139 | 38.61 | -35.70*** | 0.001 | 1.48 | 0.881 | -0.87 | 0.933 |
| | | (47.88) | (2.93) | | (3.87) | | (4.05) | |
| Max monthly WTP for perfect reliability | 3150 | 3.62 | -1.84*** | 0.001 | -0.37 | 0.622 | 0.47 | 0.365 |
| | | (4.85) | (0.22) | | (0.27) | | (0.30) | |
| Max monthly WTP for half of curr. outages | 3150 | 1.74 | -0.59*** | 0.002 | -0.18 | 0.622 | 0.22 | 0.527 |
| | | (2.98) | (0.17) | | (0.19) | | (0.22) | |
| Max monthly WTP for half of curr. volt. fluc. | 2000 | 2.14 | -0.42 | 0.218 | -0.42 | 0.622 | 0.57 | 0.365 |
| | | (3.68) | (0.30) | | (0.36) | | (0.39) | |
| Voltage damage and protection index | 3150 | 0.00 | -0.11** | 0.040 | 0.09 | 0.622 | -0.10* | 0.365 |
| | | (1.00) | (0.05) | | (0.06) | | (0.06) | |
| Any appliance damaged by voltage in past year | 3150 | 0.25 | -0.05* | 0.123 | 0.04 | 0.622 | -0.05 | 0.417 |
| | | (0.43) | (0.03) | | (0.03) | | (0.04) | |
| Amt spent on burnt/broken apps in past year | 3080 | 10.22 | -6.90*** | 0.001 | 0.25 | 0.917 | 1.15 | 0.755 |
| | | (37.23) | (1.47) | | (1.98) | | (2.05) | |
| Any voltage protective device | 3150 | 0.25 | -0.02** | 0.025 | 0.02 | 0.831 | -0.02 | 0.365 |
| | | (0.44) | (0.01) | | (0.02) | | (0.01) | |
| Value of voltage protective devices | 2668 | 6.05 | -3.06*** | 0.007 | 0.52 | 0.881 | 0.22 | 0.933 |
| | | (25.51) | (1.00) | | (1.57) | | (1.70) | |
| Uses an alternative energy source | 3150 | 0.05 | -0.01 | 0.381 | 0.00 | 0.881 | -0.00 | 0.933 |
| | | (0.22) | (0.01) | | (0.01) | | (0.01) | |
| Total number of appliances | 3150 | 8.59 | 0.04 | 0.691 | -0.10 | 0.881 | 0.08 | 0.755 |
| | | (5.98) | (0.09) | | (0.34) | | (0.13) | |
| Monthly electricity spending | 3050 | 19.51 | -6.41*** | 0.001 | -2.01* | 0.622 | 0.77 | 0.601 |
| | | (18.67) | (0.67) | | (1.12) | | (0.89) | |
| Total profit in past month | 1104 | 108.61 | -21.45** | 0.076 | -11.91 | 0.622 | 5.21 | 0.865 |
| | | (158.44) | (10.80) | | (12.02) | | (14.07) | |
| Total revenue in past month | 1280 | 436.45 | 18.37 | 0.691 | 5.87 | 0.917 | -87.44 | 0.365 |
| | | (689.48) | (43.52) | | (55.89) | | (58.15) | |
| Total monthly reported business spending | 1206 | 304.41 | 34.28 | 0.381 | 38.12 | 0.622 | -97.95** | 0.365 |
| | | (395.39) | (35.48) | | (38.04) | | (49.39) | |
| Total household monthly income | 1358 | 360.69 | -76.42** | 0.066 | 12.66 | 0.881 | -72.63 | 0.365 |
| | | (491.13) | (36.60) | | (43.51) | | (50.21) | |

Notes: This table shows the difference-in-difference results from the Equation 2 pooling businesses and households. Each row represents an outcome. All outcomes pre-specified in the pre-analysis plan (Berkouwer et al., 2019). All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Results are qualitatively unchanged when using logged versions of continuous outcomes. Sample sizes vary for some questions because of missing data, particularly when respondents were unable to estimate monetary values with a high degree of confidence, or because some questions were only asked to a subset of respondents. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is a household or a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sharpened FDR q-values following Anderson (2008) are also shown.

Table C9: Impact of transformer injection intervention on primary outcomes, accounting for implementation issues and construction timing

| | All sites | Commissioned sites (SMEC) | New tx confirmed sites | All sites, IV new tx with treat | All sites, except close sites |
|---|---|---|---|---|---|
| Reported hours of bad voltage in past month | -9.12 | -10.21 | -12.72 | -12.04 | -4.90 |
| | (7.64) | (7.75) | (7.86) | (10.04) | (8.36) |
| Reported total outage hours in past month | -0.87 | -0.98 | -2.33 | -1.16 | 4.09 |
| | (4.05) | (4.09) | (4.41) | (5.33) | (5.10) |
| Max monthly WTP for perfect reliability | 0.47 | 0.49 | 0.58* | 0.62 | 0.23 |
| | (0.30) | (0.31) | (0.33) | (0.40) | (0.38) |
| Max monthly WTP for half of curr. outages | 0.22 | 0.22 | 0.28 | 0.30 | -0.01 |
| | (0.22) | (0.22) | (0.24) | (0.29) | (0.29) |
| Max monthly WTP for half of curr. volt. fluc. | 0.57 | 0.62 | 0.76* | 0.75 | 0.25 |
| | (0.39) | (0.38) | (0.41) | (0.50) | (0.53) |
| Voltage damage and protection index | -0.10* | -0.11* | -0.13** | -0.14* | -0.16** |
| | (0.06) | (0.06) | (0.07) | (0.08) | (0.08) |
| Any appliance damaged by voltage in past year | -0.05 | -0.06 | -0.07* | -0.06 | -0.08* |
| | (0.04) | (0.04) | (0.04) | (0.05) | (0.05) |
| Amt spent on burnt/broken apps in past year | 1.15 | 0.97 | -0.01 | 1.52 | 1.54 |
| | (2.05) | (2.07) | (2.18) | (2.72) | (2.84) |
| Any voltage protective device | -0.02 | -0.01 | -0.01 | -0.02 | -0.02 |
| | (0.01) | (0.01) | (0.01) | (0.02) | (0.02) |
| Value of voltage protective devices | 0.22 | 0.17 | 1.03 | 0.30 | -1.11 |
| | (1.70) | (1.73) | (1.91) | (2.26) | (1.72) |
| Uses an alternative energy source | -0.00 | -0.00 | 0.00 | -0.00 | 0.02 |
| | (0.01) | (0.01) | (0.01) | (0.01) | (0.02) |
| Total number of appliances | 0.08 | 0.08 | 0.14 | 0.10 | 0.12 |
| | (0.13) | (0.14) | (0.14) | (0.18) | (0.16) |
| Monthly electricity spending | 0.77 | 0.74 | 0.73 | 1.02 | 0.90 |
| | (0.89) | (0.90) | (0.97) | (1.18) | (1.13) |
| Total profit in past month | 5.21 | 5.61 | 11.88 | 7.05 | 6.39 |
| | (14.07) | (14.22) | (15.19) | (18.82) | (18.81) |
| Total revenue in past month | -87.44 | -87.03 | -18.32 | -120.09 | -104.18 |
| | (58.15) | (59.03) | (58.05) | (83.21) | (71.27) |
| Total monthly reported business spending | -97.95** | -100.21** | -54.34 | -130.42* | -143.81** |
| | (49.39) | (49.90) | (49.76) | (68.44) | (59.91) |
| Total household monthly income | -72.63 | -79.87 | -84.01 | -98.25 | -51.47 |
| | (50.21) | (50.78) | (54.26) | (67.42) | (58.58) |

This table shows the same difference-in-difference analyses presented in Table B4. Column 1 replicates the 'Post × Treat' column from Table B4. Column 2 drops two sites in Kaneshie where the construction manager SMEC indicated the new transformer was not commissioned successfully. Column 3 drops sites where our own construction monitoring activities indicated no new transformer was built in a treatment site or a new transformer was built in a control site. Column 4 instruments for observing a new transformer during the construction monitoring visits with site treatment assignment. Column 5 shows the difference-in-difference results from the main equation, by dropping geographically close control sites. We define distance by the shortest path to a treatment site, and we drop ant control site that is within 1.3 km from a treatment site, where 1.3 km is the median distance to a treatment site. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C10: Impact of transformer injection intervention on main business outcomes, dropping geographically close control sites

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Total profit in past month | 1006 | 100.92 | -27.10* | 3.90 | -7.22 |
| | | [151.98] | (16.37) | (15.24) | (22.87) |
| Total monthly reported business spending | 1065 | 278.23 | 64.83 | 80.61** | -130.21** |
| | | [362.22] | (48.82) | (39.01) | (58.39) |
| Total wages and benefits paid in past month | 1118 | 57.64 | 16.07 | 5.85 | -16.54 |
| | | [142.30] | (15.10) | (13.32) | (17.16) |
| Total materials cost in past month | 1089 | 179.16 | 61.45 | 84.15*** | -116.12** |
| | | [283.70] | (37.79) | (29.81) | (46.38) |
| Monthly electricity spending | 1231 | 18.46 | -5.55*** | -1.10 | -0.34 |
| | | [19.40] | (1.03) | (1.62) | (1.21) |
| Amount spent on all alt. fuels in past month | 1256 | 4.12 | 0.45 | -0.01 | -0.86 |
| | | [11.98] | (1.12) | (0.86) | (1.34) |
| Total revenue in past month | 1088 | 394.04 | 34.99 | 63.22 | -117.17* |
| | | [553.18] | (60.59) | (53.35) | (70.78) |
| Estimated change in revenue with perfect electricity | 985 | 384.54 | -128.46* | 67.62 | -191.37* |
| | | [757.15] | (71.24) | (70.91) | (99.81) |
| Number of workers | 1256 | 1.92 | 0.06 | 0.06 | 0.12 |
| | | [1.40] | (0.09) | (0.15) | (0.11) |
| Share of men employees | 1252 | 0.31 | -0.00 | 0.01 | -0.01 |
| | | [0.42] | (0.02) | (0.02) | (0.02) |
| Share of full-time employees | 1245 | 0.90 | -0.06*** | 0.01 | 0.01 |
| | | [0.21] | (0.02) | (0.02) | (0.03) |
| Business open during any 'dark' hours | 1256 | 0.81 | -0.11*** | -0.05 | 0.00 |
| | | [0.40] | (0.03) | (0.04) | (0.04) |
| Total hours typically open | 1256 | 12.44 | -0.64*** | -0.38 | -0.10 |
| | | [2.60] | (0.16) | (0.23) | (0.24) |
| Applied for loans in past 12 months | 1256 | 0.14 | 0.02 | 0.08*** | -0.04 |
| | | [0.35] | (0.04) | (0.03) | (0.05) |
| Total value of outstanding loans | 1233 | 319.92 | 96.74 | 143.51 | -279.61** |
| | | [1213.41] | (105.84) | (113.73) | (132.18) |
| Permanently change industry/business (0-1) | 1252 | 0.02 | -0.01 | -0.01 | 0.03* |
| | | [0.14] | (0.01) | (0.01) | (0.01) |
| Permanently substitute to more labor (0-1) | 1252 | 0.00 | -0.00 | 0.01 | 0.01 |
| | | [0.07] | (0.01) | (0.01) | (0.01) |
| Permanently substitute to non-electric tools or machines (0-1) | 1252 | 0.02 | -0.01 | -0.02* | 0.01 |
| | | [0.14] | (0.01) | (0.01) | (0.01) |
| Business engaged in retail activities | 1256 | 0.43 | 0.02 | -0.00 | -0.02* |
| | | [0.50] | (0.01) | (0.05) | (0.01) |
| Business engaged in manufacturing activities | 1256 | 0.21 | 0.01 | -0.01 | 0.00 |
| | | [0.41] | (0.01) | (0.03) | (0.01) |
| Business engaged in other service activities | 1256 | 0.36 | -0.02* | 0.01 | 0.02 |
| | | [0.48] | (0.01) | (0.05) | (0.01) |
| Business activity likely using electricity | 1256 | 0.20 | 0.01 | 0.02 | -0.00 |
| | | [0.40] | (0.01) | (0.03) | (0.01) |

Notes: This table shows the difference-in-differences results from the main equation, by dropping the geographically close control sites. We define distance by the shortest path to a treatment site, and we drop any control site that is within 1.3 km from a treatment site, where 1.3 km is the median distance to a treatment site. Each row represents an outcome. In all regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is the business owner or a manager, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C11: Correlations between voltage quality and primary outcomes

| | N | Control Mean (SD) | Avg voltage (SE) | Hours below nominal-10 (SE) |
|---|---|---|---|---|
| Reported hours of bad voltage in past month | 3130 | 43.05 | -0.010*** | 0.028*** |
| | | [87.25] | (0.00) | (0.01) |
| Reported total outage hours in past month | 3092 | 32.20 | -0.009*** | 0.024*** |
| | | [31.09] | (0.00) | (0.01) |
| Max monthly WTP for perfect reliability | 3150 | 3.62 | -0.006*** | 0.014*** |
| | | [4.85] | (0.00) | (0.00) |
| Max monthly WTP for half of curr. outages | 3150 | 1.74 | -0.005*** | 0.011** |
| | | [2.98] | (0.00) | (0.00) |
| Max monthly WTP for half of curr. volt. fluc. | 2000 | 2.14 | -0.003** | 0.008 |
| | | [3.68] | (0.00) | (0.01) |
| Voltage damage and protection index | 3150 | 0.00 | -0.003* | 0.010** |
| | | [1.00] | (0.00) | (0.00) |
| Any appliance damaged by voltage in past year | 3150 | 0.25 | -0.004** | 0.010** |
| | | [0.43] | (0.00) | (0.00) |
| Amt spent on burnt/broken apps in past year | 3080 | 10.22 | -0.003** | 0.007* |
| | | [37.23] | (0.00) | (0.00) |
| Any voltage protective devices | 3150 | 0.25 | -0.000 | 0.004 |
| | | [0.44] | (0.00) | (0.00) |
| Value of voltage protective devices | 2668 | 6.05 | -0.003 | 0.008* |
| | | [25.51] | (0.00) | (0.00) |
| Uses an alternative energy source | 3150 | 0.05 | 0.000 | -0.001 |
| | | [0.22] | (0.00) | (0.00) |
| Total number of appliances | 3150 | 8.59 | 0.001 | -0.004 |
| | | [5.98] | (0.00) | (0.00) |
| Monthly electricity spending | 3050 | 19.51 | -0.001 | 0.005 |
| | | [18.67] | (0.00) | (0.00) |
| Total profit in past month | 1104 | 108.61 | -0.000 | -0.000 |
| | | [158.44] | (0.00) | (0.00) |
| Total revenue in past month | 1280 | 436.45 | 0.001 | -0.006 |
| | | [689.48] | (0.00) | (0.00) |
| Total monthly reported business spending | 1206 | 304.41 | 0.001 | -0.006 |
| | | [395.39] | (0.00) | (0.00) |
| Total household monthly income | 1358 | 360.69 | -0.002 | 0.010* |
| | | [491.13 | (0.00) | (0.01) |

Notes: This table shows the results from separate regressions of normalized outcomes on measures of voltage quality. Each row represents a different outcome pooling business and household respondents. The control mean is calculated for the original (non-normalized) outcome variable in column 2. Mean voltage in control sites is 219.5V at baseline and 224.6V at endline. Voltage is measured by assigning each respondent GridWatch data based on the nearest devices for either the last 30 days from the survey date or for the full baseline period (prior to November 1, 2020) and endline period (from April 1, 2021 - July 20, 2022). In all the regressions, we also control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the location includes both a household and a business, and district fixed effects. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

# D Appendix: Pre-specified analyses of socioeconomic outcomes

Table D1: Impact of transformer injection intervention on willingness to pay outcomes

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Max monthly WTP for perfect reliability | 3150 | 3.62 | -1.84*** | -0.37 | 0.47 |
| | | [4.85] | (0.22) | (0.27) | (0.30) |
| Max monthly WTP for half of curr. outages | 3150 | 1.74 | -0.59*** | -0.18 | 0.22 |
| | | [2.98] | (0.17) | (0.19) | (0.22) |
| Max monthly WTP for 1 unnan. 8hr outage | 906 | 1.11 | -0.55*** | -0.18 | 0.13 |
| | | [1.78] | (0.16) | (0.17) | (0.21) |
| Max monthly WTP for 1 announ. 8hr outage | 924 | 1.45 | -0.95*** | -0.05 | 0.27 |
| | | [2.22] | (0.20) | (0.24) | (0.27) |
| Max monthly WTP for 4 unnan. 2hr outages | 884 | 1.19 | -0.71*** | 0.29 | -0.19 |
| | | [2.10] | (0.15) | (0.22) | (0.23) |
| Max monthly WTP for half of curr. volt. fluc. | 2000 | 2.14 | -0.42 | -0.42 | 0.57 |
| | | [3.68] | (0.30) | (0.36) | (0.39) |
| Max WTP for generator | 2887 | 356.03 | -61.97** | 29.91 | -37.43 |
| | | [452.35] | (24.41) | (25.69) | (32.41) |

Additional results from Equation 2. All variables measuring values are in USD. Results are qualitatively unchanged when using logs. Sample sizes are lower for reliability scenarios that were only presented to a random subset of respondents. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is part of the household or business sample, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$

Table D2: Impact of transformer injection intervention on alternative energy and defensive investment outcomes

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Uses an alter. energy source | 3150 | 0.05 | -0.01 | 0.00 | -0.00 |
| | | [0.22] | (0.01) | (0.01) | (0.01) |
| Value of alter. energy sources | 3084 | 223.44 | -62.94* | 558.72 | -615.79 |
| | | [3711.51] | (35.06) | (691.33) | (641.94) |
| Count of voltage defensive invest. | 3150 | 0.35 | -0.06*** | -0.01 | 0.01 |
| | | [0.70] | (0.01) | (0.04) | (0.02) |
| Value of voltage protective devices | 2843 | 8.10 | -0.45 | -0.31 | -0.47 |
| | | [34.09] | (3.50) | (1.85) | (3.76) |
| Has multi-phase system | 2810 | 0.04 | 0.01 | 0.01 | -0.01 |
| | | [0.20] | (0.01) | (0.01) | (0.01) |
| Frequency of switching phases (z-score) | 3150 | 0.02 | -0.03 | 0.11 | -0.08 |
| | | [1.18] | (0.05) | (0.08) | (0.07) |
| Cost of installing phase system | 2732 | 10.15 | -4.14 | 3.60 | -6.59 |
| | | [110.88] | (4.47) | (6.65) | (6.19) |

Notes: This table shows the difference-in-difference results from the main equation. Each row represents an outcome. All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Results are qualitatively unchanged when using logged versions of continuous outcomes. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is part of the household or business sample, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table D3: Impact of transformer injection intervention on energy/electricity spending and burnt appliance outcomes

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Monthly electricity spending | 3098 | 19.37 | -6.26*** | -2.05* | 0.75 |
| | | [18.58] | (0.67) | (1.10) | (0.87) |
| Has generator | 3150 | 0.04 | -0.01 | -0.00 | 0.01 |
| | | [0.20] | (0.01) | (0.01) | (0.01) |
| Generator fuel and maintenance costs in past 3 months | 3150 | 5.15 | -3.89*** | -2.37 | 1.60 |
| | | [48.99] | (1.41) | (1.94) | (1.66) |
| Has solar panels | 3150 | 0.01 | -0.00 | 0.00 | -0.00 |
| | | [0.08] | (0.00) | (0.00) | (0.00) |
| Amount spent on solar panel repairs in past 3 months | 3145 | 0.52 | -0.52 | -0.53 | 0.52 |
| | | [14.41] | (0.52) | (0.52) | (0.52) |
| Count of alternative fuels used in past 3 months | 3150 | 0.92 | 0.05* | -0.01 | 0.01 |
| | | [0.85] | (0.03) | (0.03) | (0.04) |
| Amount spent on all alt. fuels in past month | 3150 | 8.73 | -0.93 | -1.53 | 0.89 |
| | | [31.42] | (1.08) | (1.23) | (1.20) |
| Amount spent on charcoal as alt. fuel in past month | 2993 | 12.21 | 13.37*** | -0.18 | -3.25 |
| | | [26.11] | (2.94) | (1.48) | (3.66) |
| Amount spent on gas as alt. fuel in past month | 2996 | 27.56 | 14.58*** | -0.73 | -0.40 |
| | | [38.74] | (2.03) | (1.94) | (4.12) |
| Amount spent on wood as alt. fuel in past month | 3140 | 5.40 | -4.28 | -5.52 | 5.64 |
| | | [144.29] | (4.42) | (5.36) | (4.51) |
| Total hrs per day lightbulbs are on | 3150 | 9.17 | -0.96*** | 0.25 | -0.58 |
| | | [5.68] | (0.34) | (0.38) | (0.46) |
| Any appliance damaged by voltage in past year | 3141 | 0.25 | -0.05* | 0.04 | -0.05 |
| | | [0.43] | (0.03) | (0.03) | (0.04) |
| Has burnt/broken apps. that were not replaced in past year | 3141 | 0.08 | -0.02* | 0.02 | -0.01 |
| | | [0.28] | (0.01) | (0.02) | (0.02) |
| Amt spent on burnt/broken apps in past year | 3114 | 10.11 | -6.82*** | 0.33 | 1.17 |
| | | [36.99] | (1.46) | (1.94) | (2.03) |

Notes: This table shows the difference-in-difference results from the main equation. Each row represents an outcome. All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Unless shown, results are qualitatively unchanged when using logged versions of continuous outcomes. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is part of the household or business sample, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table D4: Impact of transformer injection intervention on electricity-related indices

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Outage backup power index | 3150 | 0.00 | -0.06* | 0.01 | -0.01 |
| | | [1.00] | (0.04) | (0.05) | (0.04) |
| Freq. of wetcell batt./generator use during outage (normalized) | 3150 | 0.06 | -0.06 | -0.01 | 0.02 |
| | | [1.26] | (0.04) | (0.06) | (0.05) |
| Share of apps. using solar/generator during outage (normalized) | 3131 | 0.10 | -0.10 | 0.03 | -0.04 |
| | | [1.41] | (0.06) | (0.08) | (0.08) |
| Alternative energy/fuel sources index | 3150 | -0.00 | -0.04 | 0.03 | -0.03 |
| | | [1.00] | (0.05) | (0.06) | (0.07) |
| Uses an alter. energy source | 3150 | 0.05 | -0.01 | 0.00 | -0.00 |
| | | [0.22] | (0.01) | (0.01) | (0.01) |
| Count of alt. light sources (normalized) | 3150 | 0.10 | -0.11* | 0.05 | -0.05 |
| | | [1.10] | (0.06) | (0.08) | (0.09) |
| Count of alt. fuel sources (normalized) | 3150 | -0.08 | 0.06* | -0.01 | 0.01 |
| | | [0.96] | (0.03) | (0.03) | (0.05) |
| Appliance protection index | 3150 | -0.00 | -0.20*** | -0.04 | 0.07* |
| | | [1.00] | (0.03) | (0.05) | (0.04) |
| Count of voltage defensive apps. (normalized) | 3150 | 0.08 | -0.10*** | -0.02 | 0.02 |
| | | [1.11] | (0.02) | (0.06) | (0.03) |
| Has multi-phase system | 2810 | 0.04 | 0.01 | 0.01 | -0.01 |
| | | [0.20] | (0.01) | (0.01) | (0.01) |
| Share of TVs plugged to TV guard (normalized) | 877 | 2.44 | -2.42*** | -0.19 | 0.26 |
| | | [0.81] | (0.14) | (0.23) | (0.24) |
| Share of fridges plugged to fridge guard (normalized) | 805 | 1.27 | -1.36*** | -0.03 | 0.09 |
| | | [0.51] | (0.10) | (0.09) | (0.14) |

Additional results from Equation 2. The main outcomes are indices; we also show results for the index components for completeness. Indices are constructed as the sum of normalized components, and are then normalized to have mean 0 and SD 1 for control respondents in the baseline. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is part of the household or business sample, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table D5: Impact of transformer injection intervention on business outcomes

| | N | Control Mean (SD) | Post (SE) | Treat (SE) | Post x Treat (SE) |
|---|---|---|---|---|---|
| Total profit in past month | 1339 | 112.81 | -24.29** | -10.05 | -10.73 |
| | | [166.13] | (10.58) | (12.75) | (19.48) |
| Total monthly reported business spending | 1407 | 316.09 | 29.35 | 26.51 | -94.98* |
| | | [417.09] | (37.18) | (38.80) | (49.36) |
| Total wages and benefits paid in past month | 1483 | 63.89 | 8.55 | -3.40 | -9.25 |
| | | [159.07] | (9.49) | (11.53) | (12.43) |
| Total materials cost in past month | 1438 | 212.79 | 36.09 | 40.06 | -90.48** |
| | | [337.94] | (29.11) | (29.38) | (40.00) |
| Total revenue in past month | 1443 | 438.36 | 15.74 | -0.67 | -99.30* |
| | | [675.55] | (42.47) | (53.22) | (56.60) |
| Estimated change in revenue with perfect electricity | 1302 | 544.86 | -329.84*** | -102.81 | 9.04 |
| | | [1958.40] | (118.00) | (132.79) | (138.45) |
| Number of workers | 1658 | 1.99 | 0.11* | -0.02 | 0.07 |
| | | [1.90] | (0.06) | (0.13) | (0.09) |
| Share of men employees | 1652 | 0.31 | -0.01 | 0.00 | 0.00 |
| | | [0.42] | (0.01) | (0.01) | (0.02) |
| Share of full-time employees | 1643 | 0.91 | -0.05*** | 0.01 | -0.00 |
| | | [0.21] | (0.02) | (0.02) | (0.02) |
| Business open during any 'dark' hours | 1658 | 0.77 | -0.08*** | -0.01 | -0.02 |
| | | [0.42] | (0.03) | (0.03) | (0.04) |
| Total hours typically open | 1658 | 12.16 | -0.58*** | -0.13 | -0.16 |
| | | [2.46] | (0.13) | (0.19) | (0.22) |
| Temporary busines response type index | 1658 | 0.00 | -0.09 | 0.02 | 0.07 |
| | | [0.73] | (0.06) | (0.08) | (0.10) |
| Temporary switch to alternative energy due to reliability (0-2) | 1652 | 0.06 | 0.04** | 0.01 | -0.01 |
| | | [0.30] | (0.02) | (0.02) | (0.03) |
| Temporary stop working, work less due to reliability (0-2) | 1652 | 0.43 | -0.03 | 0.01 | -0.01 |
| | | [0.71] | (0.04) | (0.06) | (0.06) |
| Temporary postpone working, work same due to reliability (0-2) | 1652 | 0.33 | -0.12*** | -0.02 | -0.01 |
| | | [0.63] | (0.03) | (0.05) | (0.05) |
| Temporary switch tools/labor due to reliability (0-2) | 1652 | 0.16 | 0.02 | -0.01 | 0.03 |
| | | [0.44] | (0.03) | (0.03) | (0.04) |
| Temporary switch business activities due to reliability (0-2) | 1652 | 0.15 | -0.03 | 0.02 | 0.04 |
| | | [0.41] | (0.03) | (0.03) | (0.04) |
| Temporary reduce labor due to reliability (0-2) | 1652 | 0.21 | -0.05 | 0.01 | 0.02 |
| | | [0.49] | (0.04) | (0.04) | (0.05) |
| Other temporary response due to reliability | 1652 | 0.02 | -0.02* | 0.00 | 0.02 |
| | | [0.17] | (0.01) | (0.01) | (0.02) |
| Temporary business response intensity index | 1658 | -0.17 | -0.32*** | 0.62 | -0.61 |
| | | [0.79] | (0.06) | (0.42) | (0.41) |
| Days of switching to solar energy | 1658 | 0.00 | -0.00 | 0.00 | 0.00 |
| | | [0.02] | (0.00) | (0.00) | (0.00) |
| Days of switching to generator | 1658 | 0.01 | -0.01* | 0.04 | -0.05 |
| | | [0.06] | (0.00) | (0.04) | (0.04) |
| Days of switching to wetcell | 1658 | 0.00 | -0.00 | 0.01 | -0.01 |
| | | [0.01] | (0.00) | (0.01) | (0.01) |
| Days stopping or postponing work in past 1 month | 1658 | -0.18 | -0.32*** | 0.01 | -0.01 |
| | | [0.75] | (0.05) | (0.07) | (0.07) |
| Percentage of business hours stopping work | 1658 | -0.19 | -0.34*** | 0.08 | -0.07 |
| | | [0.75] | (0.06) | (0.09) | (0.09) |
| Permanent business response index | 1658 | 0.00 | -0.12* | -0.09 | 0.27** |
| | | [0.73] | (0.07) | (0.07) | (0.12) |
| Permanently substitute to non-electric tools or machines (0-1) | 1652 | 0.02 | -0.01 | -0.01** | 0.01 |
| | | [0.13] | (0.01) | (0.01) | (0.01) |
| Permanently substitute to more labor (0-1) | 1652 | 0.01 | -0.01 | 0.00 | 0.02 |
| | | [0.09] | (0.00) | (0.01) | (0.01) |
| Permanently change industry/business (0-1) | 1652 | 0.01 | -0.01 | -0.01 | 0.03** |
| | | [0.12] | (0.01) | (0.01) | (0.01) |
| Purchase generator (0-1) | 1652 | 0.01 | -0.01 | -0.01 | 0.01 |
| | | [0.12] | (0.01) | (0.01) | (0.01) |
| Business qualitative assessments index | 1658 | -0.05 | -0.76*** | 0.02 | -0.06 |
| | | [0.89] | (0.07) | (0.08) | (0.09) |
| Perceived safety in area (1-5) | 1657 | 3.40 | 0.02 | -0.06 | 0.15 |
| | | [1.02] | (0.08) | (0.10) | (0.11) |
| Importance of electricity as obstacle to business (1-5) | 1652 | 3.89 | -0.23*** | 0.03 | -0.07 |
| | | [0.99] | (0.08) | (0.08) | (0.11) |
| Belief that Dumsor is back (1-5) | 1652 | 2.91 | 1.49*** | 0.12 | -0.05 |
| | | [1.29] | (0.10) | (0.11) | (0.12) |
| Expected reliability one year from today (1-3) | 1338 | 2.34 | 0.30*** | -0.02 | 0.08 |
| | | [0.80] | (0.07) | (0.07) | (0.09) |
| Importance of finance/access to credit as a business obstacle (1-5) | 1658 | 2.79 | -0.38*** | 0.02 | 0.11 |
| | | [1.29] | (0.11) | (0.10) | (0.15) |

Additional results from Equation 2. All variables measuring values are in USD. Results are qualitatively unchanged when using logs. All regressions control for baseline socioeconomic characteristics. The control mean is for the baseline period. SEs clustered by site. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$