

Voltage quality and economic activity

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Abstract

While voltage problems are believed to be ubiquitous in low-income countries, the impact of voltage quality on the economy is understudied. Novel minute-by-minute customer-level power measurements linked to panel surveys in urban Ghana reveal systematic under-voltage, damaging equipment and incentivizing protective investments. Customers would pay 10% more for electricity with better voltage. Quasi-random grid improvements raised average voltage by 5.5V, reducing appliance damages, but yielded minimal economic impacts after one year. Investments may generate longer-run returns—for example, after customers upgrade appliances—pointing to the complexity of allocating long-term investments with short-term data. We provide a framework for evaluating power grid 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 in recent years greatly enhanced researchers’ abilities to assess the technological determinants of economic performance—including the functioning of the energy grid, the bedrock of every modern economy. In addition to studies on electricity pricing and access, among other topics, these novel data sources have enabled extensive analyses of the economic cost of power outages.¹ Widespread power outages have caused deaths and economic crises across the world in for example California, Texas, and Ghana (Abeberese, 2019; Abeberese et al., 2021; Svitek, 2024; Wolfram, 2019). This paper uses customer surveys and high-frequency sensor data collected over several years to analyze an understudied feature of modern energy grids: voltage quality. Voltage problems such as fluctuations and persistent sags can damage appliances and limit appliance functionality, imposing economic costs and affecting electricity use. However, these costs are poorly understood due to a lack of high-resolution voltage data in contexts with poor voltage.

In most countries, electric utilities are charged with providing electricity within $\pm 10\%$ of targeted voltage—for example, 120 volts (V) in the US and 230V in Ghana—so that customers can operate machinery and appliances efficiently and without damage (CENELEC, 2006). Utilities in low-resource contexts often fail to meet these standards. Yet, voltage issues continue to be deprioritized in policy and regulatory debates. The United Nations Sustainable Development Goal 7—“*affordable, reliable, sustainable and modern energy for all*”—does not mention voltage (UN, 2022). World Bank reports often either do not discuss voltage or depend on household self-reports, which can be inaccurate (WB, 2020, 2021). Understanding the economic costs of poor voltage quality—in particular relative to improvements in access, reliability, or affordability—is crucial in enabling resource-constrained utilities to optimally target grid investments.

We analyze 337 million customer-level electricity reliability and voltage measurements, collected from more than 1,000 utility customers over the span of six years, and survey data from over 2,000 households and firms in Accra, Ghana, to generate some of the first evidence on the large-scale economic costs of poor voltage quality. We first characterize voltage quality concerns and their associated economic costs, and then estimate the causal impact of a quasi-random \$13.9 million investment in electricity grid infrastructure on electricity quality and socioeconomic outcomes.

The analyses generate three key findings. First, we document significant voltage problems. Average voltage at baseline—before grid infrastructure investments were completed—is 219V, significantly lower than the targeted nominal level of 230V. Voltage is more than 10% (20%) below the nominal level for 5.3 (1.2) hours per day. Customers experience an average of 250 low-voltage ‘spells’ each month, lasting more than 130 hours in total. Such fluctuations can damage commercial

¹On outages: Allcott et al. (2016), Fisher-Vanden et al. (2015), Gertler et al. (2017), and Hardy and McCasland (2019). 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).

and residential appliances: machinery cannot operate at full capacity, and protective components can malfunction, damaging appliances.²

Second, these voltage issues are salient to respondents and bring economic costs. Respondents would be willing to pay an additional 10% per month in electricity costs if their connection had no voltage fluctuations, and 19% more per month if it also had no power outages. One-third of firms report voltage to be an important obstacle to operations. A quarter of respondents own devices to protect appliances against bad voltage, valued at \$56 on average (approximately 15% of both monthly household income and monthly firm revenues in the sample). Despite such investments, 25% of respondents report that at least one appliance was damaged due to bad voltage in the last year, costing an average of \$41 to repair or replace.

Finally, we use a difference-in-differences approach to assess the effects of voltage quality improvements, comparing 76 sites where a new transformer was installed to 75 comparable sites without such an investment. While the control group's average voltage rose from 219V to 225V (due to concurrent grid infrastructure investments), the treatment group's voltage increased from 219V to nearly the targeted 230V. The intervention thus increased average voltage by 5.5V in the treatment group relative to the control group, reducing time spent with low-quality voltage by 55 hours per month, but had no effect on outage duration.

The treatment leads to a modest reduction in voltage-related damages and ownership of protective devices. However, it has no significant effect on other household or business outcomes in the 16 months following the voltage improvements. There is no significant impact on appliance ownership during this period, which could explain the absence of major effects on broader socioeconomic indicators such as electricity spending, firm profits, and household income.

These findings present a puzzle. The line bifurcation treatment significantly improved power quality, yet these improvements have limited socioeconomic impact in the medium term. This raises the question: what explains the lack of significant socioeconomic effects?

It is possible that improved power quality simply has limited benefits for customers in the study sample. However, voltage issues are salient to customers, and they are willing to pay more for higher-quality power. They also face significant costs from appliance damages and investment in protective devices. These suggest that at least some customers should benefit from improved voltage. Yet, we find no impacts even among respondents more vulnerable to poor power quality.

Alternatively, voltage improvement impacts may be non-linear (and the marginal effect at higher levels lower), or the economic impacts may have been too small for us to be able to statistically detect. However, extensive heterogeneity checks suggest otherwise: excluding the 25% of control sites with the largest voltage improvements yields an 11V treatment effect on average voltage, but does not increase the estimated socioeconomic impacts. We also find no heterogeneity in impacts by baseline levels of voltage quality.

One possibility that more closely matches our empirical findings is that the economic benefits

²Elphick 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” (p. 576).

of voltage improvements stem primarily from capital investments in new appliances and machinery, which may not materialize within 16 months of the intervention. Consumers might need time to be able to afford appliance upgrades, or they may delay such investments until they are confident that the improvements are sustained, particularly given Ghana’s history of fluctuating power reliability in the preceding decade. Consistent with this hypothesis, we find economically large but statistically imprecise evidence that customers at treated sites are more likely to be planning a new appliance purchase at endline. While low voltage imposes significant costs that consumers are willing to pay to mitigate, investment decisions may exhibit inertia, leading to delayed behavioral responses. If this mechanism is at play, utilities implementing such grid investments should anticipate that any economic benefits may take time to materialize.

These analyses offer a framework to evaluate power distribution network improvements. On the one hand, within the 16 month timeframe of this study, the economic benefits accruing to customers in the study area do not appear to exceed the investment’s \$13.9 million cost. On the other hand, infrastructure investments often generate returns over decades, not months: our results suggest long-term effects are still plausible. Governments and donors face significant constraints when choosing long-run investments such as grid expansions to communities without connections, generation capacity expansions to support the continuous operation of high-utilization equipment, or distribution network improvements to enhance voltage quality and power reliability. Utilities are required to make allocation decisions without the ability to observe their long-term impacts. Analyzing the short-term impacts of grid investments on voltage quality is a first step in understanding their long-term impacts on economic well-being.

This paper builds on a small set of research papers on voltage quality issues in low- and middle-income countries. 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). Jacome et al. (2019) directly measure voltage levels among 25 households in Tanzania and find that average voltage is often more than 10% below nominal. Meeks et al. (2023) randomize smart meter installation across 20 transformers in Kyrgyzstan to document that metered residential electricity consumption increases in response to voltage improvements.

More broadly, this paper expands our understanding of the economic impacts of infrastructure quality in low- and middle-income countries, and in particular when construction is outsourced to the private sector (Gertler et al., 2022; Hallegatte et al., 2019; Rentschler et al., 2019). Infrastructure quality has historically been difficult to study due to data limitations, as related data are often provided by the state and may therefore not be suitable for independent quality evaluation. We contribute to a literature that collects fine-grained data on publicly-provided infrastructure independently from the public sector (Olken, 2007; Wolfram et al., 2023), and present new estimates of the economic costs of an understudied aspect of modern infrastructure.

2 Voltage quality: importance and measurement challenges

Existing global energy policy focuses overwhelmingly on access and reliability. The World Bank’s Energy Sector Management Assistance Program Multi-Tier Framework quantifies these dimensions in nuanced detail, delineating 12 categories of capacity and 10 categories of availability, with metrics for each category (ESMAP, 2015): for example, the ‘availability’ category contains five tiers for daily availability and five tiers for evening availability.

However, it only defines two coarse tiers of voltage quality: “voltage problems that damage appliances” and “voltage problems do not affect the use of desired appliances” (ESMAP, 2015). Yet even this imprecise definition of voltage quality is difficult to measure. This very coarse categorization of what is a highly complex phenomenon may be driven by limited data availability on voltage. Without granular data, voltage quality cannot be adequately factored into grid planning or tracked using development indicators.

As a result, the economic implications of poor voltage quality have received little attention. Much of the existing evidence is anecdotal or based on survey reports (Blimpo and Cosgrove-Davies, 2019; Dubey, 2020), with few studies able to collect and analyze detailed measures of customer-level voltage quality. Jacome et al. (2019) measure voltage quality for 25 households in Unguja, Tanzania, and find that customers near the end of the line 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.

Utility regulators normally set a target voltage for electricity distribution, and limit the amount of time that voltage, as experienced by customers, can deviate from the nominal voltage level by more than $\pm 10\%$. Appliances are designed to be used on grids that provide voltage in this range. Most of the world’s population—including Ghana—has a nominal voltage of 230V (IEC, 2023). Meeting these requirements is critical to ensuring a high-quality electricity supply, and maintaining secure and stable power systems, which is critical for any modern economic activity (IEA, 2022).

Voltage in low- and middle-income country (LMIC) contexts often falls outside the nominal range. However, a lack of large-scale data has limited research on the broader economic impacts of poor voltage quality. Most utilities and regulators have no way of measuring voltage as experienced by customers.³ This problem is exacerbated in LMICs, where resource constraints prevent utilities from investing in improved technologies: the widespread deployment of smart meters, for example, can be prohibitively expensive (Dutta and Klugman, 2021).

³Many utilities have substation-level monitoring systems, but these only detect outages at high- or medium-voltage transmission levels (while outages emerging at the low-voltage customer distribution level can comprise a large share of power outages), and do not measure customer-level voltage. Transformer-level systems also do not capture customer-level electricity quality.

2.1 Types of voltage quality issues

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. Some will experience failure of protective components, even as other components continue to function, burning appliances. Voltage spikes—extreme increases often lasting seconds or less—can also cause significant damages to plugged-in appliances. These are rare but sometimes occur as power returns after an outage. Over-voltage spells—modest but longer-lasting increases above the nominal voltage range—are less damaging than under-voltage spells 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. The amount of power used by an appliance (in watts) is a combination of voltage (in volts) and current (in amperes). Counterintuitively, voltage *drops* can cause appliances to burn, either because the drop in voltage prevents protective components of appliances to function properly (causing other components to operate without necessary protections), or because the appliance draws in additional current to compensate for the drop in voltage. These processes furthermore vary significantly across appliances, depending on what electrical components the appliance contains.⁴ A single short but large voltage spike or sag can cause more damage than a more moderate but lengthier under- or over-voltage spell, but a simple average voltage metric will not capture this non-linearity. Fluctuations may also affect appliances differently than under- or over-voltage spells. Unlike reliability, where the System Average Interruption Duration Index (SAIDI) is a globally and industry-wide accepted indicator (Ayaburi et al., 2020; Vugrin et al., 2017), existing indicators for voltage quality do not accurately capture voltage issues common in low-resource settings, instead applying more to high-income settings with only minimal deviations from nominal (IEEE, 2018).

To characterize voltage quality, we define and analyze several metrics: average voltage, time spent outside of certain voltage thresholds, the count of under-voltage spells, the duration of under-voltage spells, and the intensity of voltage spells as measured by minimum voltage reached.

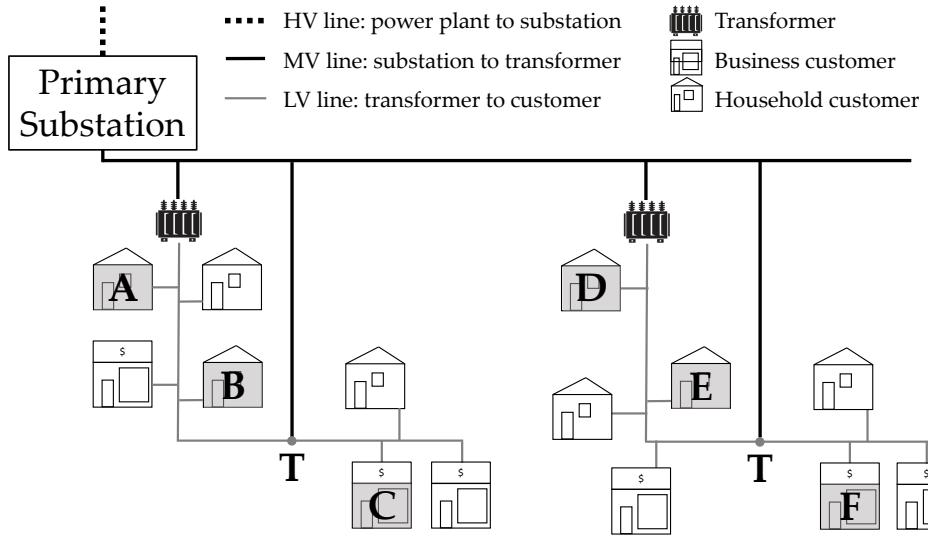
2.2 Causes of poor voltage quality

In most countries, high voltage (HV) cables transmit electricity from power stations to primary substations. Medium voltage (MV) cables then transmit this electricity on to distribution transformers, and low voltage (LV) distribution lines then distribute power 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. As load increases, the transformer’s output voltage drops, causing voltage to drop. Load variability therefore also increases customer voltage variability. If the transformer is overloaded—that is, when load exceeds transformer capacity—output voltage can drop below the target voltage range.

⁴This can include, for example, motors, lighting, power electronic devices, or resistive elements (McKenna and Keane, 2016).

Figure 1: Schematic of an electricity distribution network



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

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 (Bailey et al., 2023; Jacome et al., 2019; Wolfram et al., 2023). The electricity grid intervention that we study (which we discuss in detail in Section 5) adds (or ‘injects’) 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 D experience similar voltage because both are near the transformer, and their transformers have a similar load. E might experience worse voltage than D because they are farther from their transformer, but better voltage than B because there are fewer customers between E and the transformer than between B and the transformer. Adding two new transformers at T should improve electricity quality for C and F, and likely for B and E, by reducing the distance to their nearest transformer. It might also improve power for A and D by reducing the load on their nearest transformer.

Baseline customer socio-economic characteristics are not strongly correlated with power quality: an index of customer wealth (proxied by structure quality, appliance ownership, and education) is not significantly associated with either bad voltage or outage hours ([Table B1](#)). This suggests that customers in our sample are not sorting on attributes. Distance to the nearest transformer is the strongest predictor of voltage quality: being 100 meters farther away is associated with 22 additional hours with voltage $>10\%$ below nominal per month ([Figure A1](#) reveals a non-linear relationship). Outage hours also increase with distance to the nearest transformer.

Power outages can also impact voltage quality, through transient spikes that occur at the inception and restoration of outages, causing significant damage to appliances. These phenomena are of very short duration and will not be captured in the voltage measurements we consider here, and are also not expected to lessen as a result of transformer injections. Other unobserved aspects

of grid quality—such as phases, household connection quality, and informal connections—also likely affect voltage quality and socio-economic outcomes.

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, 2019; Abeberese et al., 2021; Briggs, 2021; Hardy and McCasland, 2019; Yakubu et al., 2018).⁵ Access and reliability have improved significantly in Ghana in recent years, with household electricity access now 86% (SE4All, 2022; Kumi, 2020) and outage duration down to 30 minutes per day per our data. 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 five years suggest they are of similar importance to customers (Figure A2).

We collaborated with engineers to deploy 1,124 GridWatch devices collecting minute-by-minute power quality data with customers residing across the Accra metropolitan region starting in 2018 (Figure A3 shows a picture of the device).⁶ Each device is plugged in with either a household or firm connected to the electricity grid.⁷ This generates 337 million data points on voltage and outages as experienced by households and firms. To the best of our knowledge, this was the first large-scale collection of customer-level outage and voltage data in any low- or middle-income country.⁸

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. 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 firm and household surveys in Accra find that wide voltage ratings (such as 100–240V) for major appliances are rare, though ranges listed on devices may be conservative. Voltage stabilizers, typically rated for 140–260V or 105–280V in Ghana, can be used to modify incoming voltage. Ghana's public utilities regulator

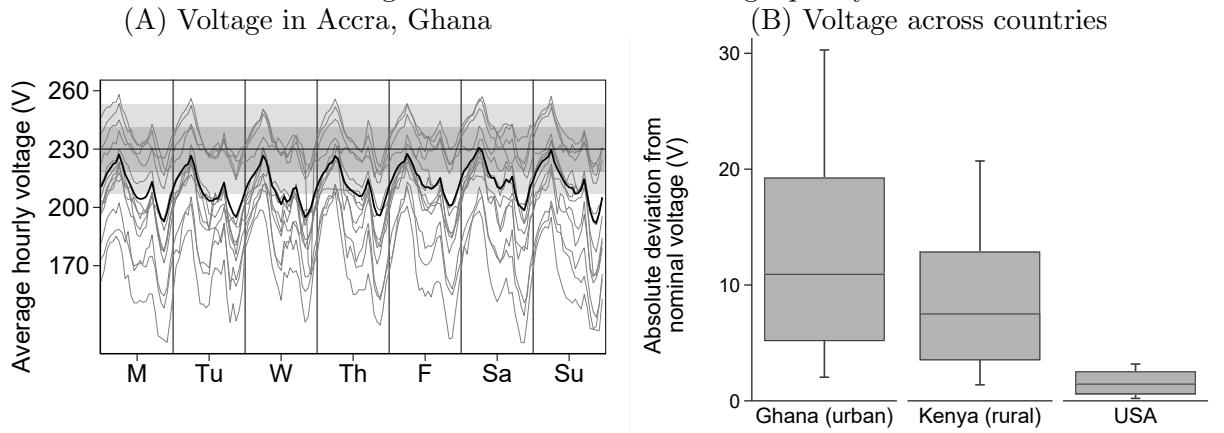
⁵At the height of the crisis, consumers faced 24-hour power cuts every 36-hour period (Mensah, 2018; Prempeh, 2020). Using data on outages at the electricity feeder (MV) level from the electricity utility in Accra, we find a peak of over 250 outage hours per month on average in July 2015, and over 100 outage hours per month for all of 2015.

⁶Devices were deployed to customers residing near the locations of potential grid infrastructure investments, which we describe further in Section 5. The devices do not capture very short sags or swells that last only a few cycles or seconds. This would require high frequency, continuous waveform monitoring, such as those provided by significantly more expensive power quality monitors. However, line bifurcation likely will not reduce these extreme events as these are mitigated by other investments (such as fuses and switches). Klugman et al. (2019) and Klugman et al. (2021) provide more information on the technology and the deployment.

⁷Each participant receives financial compensation for each month they keep the device plugged in. Section 5 presents more information on site and respondent selection.

⁸Jacome et al. (2019) measure customer-level voltage levels among 25 households in rural Tanzania.

Figure 2: Customer-level voltage quality



Panel A: Voltage measurements for 20 randomly selected participants for an arbitrarily chosen week in April 2020. The bold line displays the average over the entire sample. The gray horizontal bands indicate $\pm 5\%$ and $\pm 10\%$ 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).

specifies that electric utilities must provide electricity with sustained voltages between $\pm 10\%$ of nominal, allowing for larger deviations only for very short duration (PURC, 2005).

Actual voltage deviates substantially from these targets. Panel A of Figure 2 displays data for 20 devices. Several patterns are worth highlighting. First, there is significant heterogeneity in average voltage across customers, which as discussed in Subsection 2.2 may reflect differences in distance to the nearest transformer and in transformer load (Figure A1). Second, customers often experience fluctuations outside the recommended range. Third, voltage is consistently worst between 7–10pm, when load is likely highest. Fourth, nearly all deviations outside the nominal range constitute voltage drops.

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 statistics for several voltage quality indicators designed to give a comprehensive picture of customer-level voltage quality, over the period from March 2019–November 2020 (before local grid improvements). Average voltage was 219V, outside the voltage rating range for most appliances in Ghana (220–240V). The median absolute deviation from nominal voltage was 12V, driven primarily by low-voltage spells. In a given hour, voltage was on average 10–20% below nominal 17% of the time and more than 20% below nominal 5% of the time. During peak load periods, the fraction of time more than 10% below nominal exceeds 30%. Voltage quality issues are significantly more common than power outages, which occur 3% of the time (14 hours per month).

Panel B presents data at the monthly level, which enables a characterization of the frequency and duration of sustained under-voltage spells. 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

Table 1: Summary statistics for 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
Mean voltage during hour (7-10pm)	209.69	23.63	23	197	213	226	409
Mean absolute deviation from nominal	16.88	17.38	0	6	12	22	207
Mean absolute deviation from nominal (7-10pm)	23.28	20.74	0	8	17	33	207
Any voltage >20% below nominal	0.09	0.28	0	0	0	0	1
Any voltage >20% below nominal (7-10pm)	0.19	0.39	0	0	0	0	1
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
SD voltage during hour	2.59	3.02	0	1	2	3	159

(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 power quality measured by 441 devices across 138 sites between March 2019 and November 2020 (before transformer injections). Outages are identified at the site level. *Panel A*: 2,872,508 device-hour observations, each computed from thirty 2-minute observations. *Panel B*: 6,871 device-month observations, summing either hourly values by device within each month (rows 1) or across individual low-voltage spells recorded by device within each month (rows 2–7). Low-voltage spells are periods with voltage <207V for at least two minutes.

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 under-voltage spells 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 devices designed to protect against voltage fluctuations (such as voltage stabilizers) or in backup energy sources. Finally, these mechanisms may lower long-term appliances investment by lowering

their expected value.

To examine the economic costs of poor voltage quality, we survey 2,001 electricity grid customers—997 households and 1,004 firms—across 151 distinct study sites in Accra where GridWatch devices were deployed. As we discuss extensively in [Section 5](#), these sites are the locations of potential new transformers. To ensure data collected by the devices reflected power quality experienced by survey respondents, respondents and devices were located very close together (see [Figure A6](#) for an example map).⁹ Per data from the Ghana Statistical Service, sample respondents are largely representative of households and firms in the Accra Metropolitan Area ([Table 4](#)). Because the new transformer investments largely targeted mixed residential and business areas, firms 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 slightly lower than the Accra median. The most common firm 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%).

4.1 Customer self-reports of reliability issues and associated costs

The baseline surveys that were conducted in March–April 2021 reveal that respondents face poor power quality. Panel A of [Table 2](#) shows that respondents report experiencing 39 hours of outages and 48 hours of bad voltage in the past month. In addition, 26% of respondents reported having voltage-related damage in the past 12 months, as a result of which they spent USD 41 to repair or replace broken appliances (around 2.5 months of average electricity spending, or around 12% of monthly household income and firm revenue).

To protect against these damages, customers purchase equipment that protects appliances from bad voltage: 25% of respondents have at least one voltage protective device, with an average estimated value of \$56.¹⁰ 92% (31%) of firms report that outages (voltage fluctuations) are an obstacle to firm 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.

Would customers prefer a utility to invest in reliability or voltage improvements? 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 currently spend), first asking about a randomly chosen price and then iteratively asking about either higher or lower prices based on the prior response.¹¹ Panel C of [Table 2](#) shows that respondents are willing to pay on average an additional \$3.3 per month (a 19% increase in electricity spending) for access to an electricity connection with no voltage fluctuations

⁹To avoid survey fatigue, there is no overlap between participants with devices and survey respondents.

¹⁰These include general purpose voltage stabilizers (15% of customers) as well as more specialized devices such as fridge guards (11%) and TV guards (4%).

¹¹This 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](#)).

Table 2: Baseline household and firm electricity quality issues

	Mean	SD	Min	25 th	50 th	75 th	Max	N
<i>Panel (A) Experience with outages and voltage</i>								
Reported number of outages in past month	6.86	5.50	0	4	6	8	90	2001
Reported total outage hours in past month	39.15	47.71	0	12	24	48	300	2001
Reported hours of bad voltage in past month	47.72	100.34	0	0	15	60	720	1988
<i>Panel (B) Economic impacts</i>								
Any voltage-related damage, last 12 months (=1)	0.26	0.44	0	0	0	1	1	2001
Amt. spent on burnt/broken apps in past year (\$)	41.43	129.49	0	0	11	40	2389	511
Any reliability protective device owned (=1)	0.25	0.43	0	0	0	0	1	2001
Value of protective devices owned (\$)	55.71	110.43	2	14	24	53	1290	261
Any alt. energy source used in last month (=1)	0.05	0.21	0	0	0	0	1	2001
Outages are obstacle to business (=1)	0.92	0.28	0	1	1	1	1	975
Voltage fluctuations are obstacle to business (=1)	0.31	0.46	0	0	0	1	1	975
<i>Panel (C) WTP for improved service quality</i>								
WTP for perfect reliability and quality (\$)	3.25	5.01	0	0	2	5	72	2001
WTP for perfect voltage and half outage hours (\$)	1.54	3.14	0	0	0	2	56	1964
WTP for no outages and half bad voltage hours (\$)	1.80	4.10	0	0	0	2	48	512
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

Spending on burnt appliances is among those with voltage-related damage. Value of voltage protective devices is among those with any such devices. Reliability protective devices include voltage stabilizers, fridge guards, and TV guards. Alternative energy sources include generators, solar panels, and wet cell batteries. WTP values are monthly amounts for an electricity connection with particular characteristics. Only a subset of respondents in the baseline survey were asked their WTP for reduced bad voltage hours. Data on share of government investment comes from the endline survey (not asked in the baseline survey) and omits respondents that equally allocated the hypothetical investment across all 5 areas. All statistics pool household and business customers but are broadly similar when considering each separately.

or outages. This includes around 30% of respondents with 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—\$1.5 and \$1.8 per month, respectively, representing around 10% of monthly electricity spending ([Figure A4](#) presents the full distributions). WTP does not appear correlated with appliance or lightbulb type ownership ([Figure A5](#)).

We also ask respondents how they would prioritize the allocation of hypothetical government funds across five public spending categories: 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 quality, similar to the mean amount allocated to reducing outages (17%).¹² Improving schools (29% of the funds)

¹²The question on allocation of government funds follows the willingness to pay for improved electricity questions as well as modules on appliance ownership and damages, outage and voltage experiences, and alternative energy use. It is possible that respondents have been primed to focus on electricity issues which could bias the share of

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 (The 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 indicates that poor voltage quality may impose costs of a similar magnitude.

4.2 Correlates of customer-level power quality and reliability

To examine how voltage quality correlates with respondent outcomes, we match each survey respondent with their nearest device. Since respondents and devices were deployed in clusters ('sites'), respondents and devices are generally located close together and often connected to the same or neighboring segments of the LV network (Figure A6). The median distance between a respondent and their matched device is 88 meters, and 80% of the respondents are within 157 meters of their matched device (Figure A7). The distributions of baseline distances to the nearest existing transformer are nearly identical for survey respondents and matched devices (Figure C5).

Such spatial proximity means power quality measured by the devices is a reasonable proxy for power quality experienced by survey respondents. The correlation in hourly voltage data between pairs of devices decreases with distance, but devices that are located within 100 meters of each other have an average correlation coefficient of 0.7 (Figure C2). There is a strong correlation between self-reported outage hours with device-measured outage hours (Panel A of Figure A8). The correlation between reported hours of bad voltage and device-measured hours when voltage was >20% below nominal is somewhat weaker, with respondents underestimating recent hours of bad voltage in situations where power quality is very bad and overestimating them when power is better (Panel B of Figure A8).

The weaker correlation for voltage may have several explanations. Individuals may only be able to detect voltage problems when voltage drops farther below the threshold of 20% below nominal voltage we use to proxy 'bad' voltage with the device data. They may also not observe voltage issues during periods they are not actively using appliances that are sensitive to voltage.¹³

Since distance to the nearest transformer is a key determinant of customer voltage quality, we create an adjusted voltage measurement that accounts for the difference in distance to transformer between the respondent and their matched device and thus generates a more accurate measure of respondent power quality.¹⁴ This adjusted voltage quality measure is more accurately correlated

funds allocated to these services upward. However, it should not bias funds allocated to improved voltage relative to reduced outages as respondents will have been similarly primed to think about both types of issues.

¹³Flickering of lights and appliances not turning on are key indicators of bad voltage, but they only occur when voltage drops significantly beyond 10% below nominal voltage and will be most visible at night. In addition, low voltage may be more noticeable with incandescent lightbulbs than with CFLs or LEDs. Only 3% of respondents own incandescent bulbs, while 28% own CFLs and 82% own LEDs (enumerators showed respondents pictures of each lightbulb type to ensure these were coded correctly). This is likely a result of concerted efforts by the utility to switch customers to more energy efficient technologies in order to avert excess load that drove power outages during the Dumsor crisis (Ghana Energy Commission, 2009).

¹⁴Specifically, we estimate the overall relationship between distance to the nearest transformer and voltage quality,

Table 3: Correlations between voltage quality and selected outcomes

	Full N	Mean (SD)	Adjusted average voltage	Adjusted hours voltage 20% below nominal
Voltage damage and protection index	3057	-0.02 (0.97)	-0.003* (0.002)	0.001** (0.001)
Amt. spent on burnt/broken apps in past year (USD)	2989	6.56 (22.94)	-0.083*** (0.029)	0.017** (0.008)
WTP for perfect reliability and quality (USD)	3057	2.50 (3.46)	-0.019*** (0.005)	0.003*** (0.001)
Total no. of appliances owned	3057	8.53 (5.42)	0.003 (0.007)	0.000 (0.002)
Last month business revenue (USD)	1245	392.85 (574.60)	1.873** (0.901)	-0.355* (0.213)

This table shows estimates from ten regressions with two voltage measurements as the explanatory variables and each row a different outcome variables, pooling firm and household respondents. Voltage measures are for the year preceding the survey date, adjusted to account for differences between the distance to the nearest transformer for the respondent and their matched device. Regressions include socioeconomic controls and district fixed effects. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ [Table B3](#) presents additional outcomes. [Table C10](#) shows the same using raw matched device data: the estimates and standard errors are very similar.

with self-reported power quality (Panel C of [Figure A8](#)), without meaningfully affecting standard errors (compare [Table 3](#) and [Table C10](#)).

[Table 3](#) shows that better voltage quality over the previous year is correlated with lower probability of appliance damage and associated expenses, and with lower WTP for improved electricity connections. We also find a marginally significant relationship between firm revenue and voltage quality: firms with 11V higher average voltage (the difference between average voltage of 219V and nominal voltage of 230V) earn on average USD 20.6 more per month. This could reflect either firm sorting on voltage quality or a causal effect of power quality on revenues. However, we find no relationship between bad voltage quality and appliance ownership or other outcomes such as protective device ownership, use of non-grid energy sources, electricity spending, household income, or business profits ([Table B3](#)). Appliance ownership among respondents may be too low for sorting on voltage to be worthwhile, or customers may face difficulties in observing local differences in power quality.

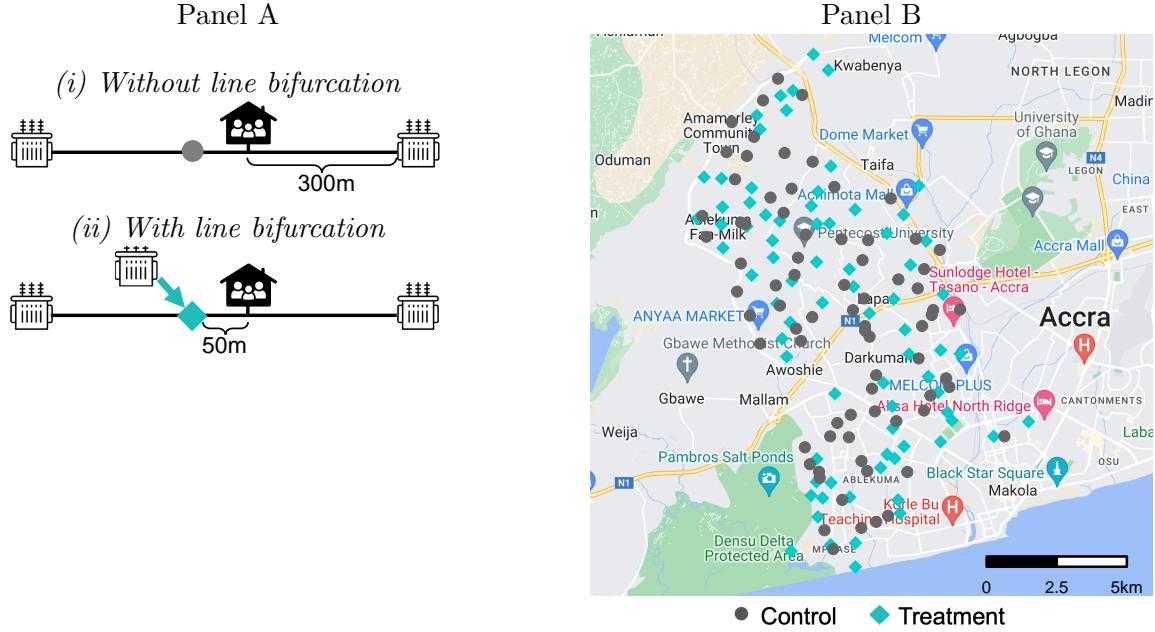
5 Identifying the causal impact of grid investments

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](#)).¹⁵ \$13.9 million was spent on “low-voltage (LV) line bifurcation” in three districts of Accra: Achimota, Dansoman, and Kanesie. We estimate the effects of this investment on power quality and

storing the residuals. We then project this relationship onto respondent distance, and then re-apply the original residuals.

¹⁵The original amount was \$498 million but this was reduced to \$316 million in 2019 (MCC, [2022](#)).

Figure 3: Line bifurcation control and treatment sites across Accra



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.

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, in particular for customers whose distance to the nearest transformer decreases the most.¹⁶

An MCC contractor selected the new transformer locations, targeting segments on the grid that were approximately 200 to 300 meters from the nearest existing transformer. Other than this distance criterion, the contractor 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 of metered connections, bill payment rates, or electricity demand (sub-district electricity data in general is largely unavailable—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

¹⁶In the long term, customers may respond to improved electricity quality by increasing usage, which would worsen voltage quality. This should be weighed against the reduction in transformer load in the short term.

a crude and noisy measure of load. Extensive discussions with representatives from MCC and the contractor confirmed that, conditional on distance to the nearest transformer, line bifurcation treatment sites were selected without obvious regard for the outcomes we study.

This decision-making process for the placement of new transformers created quasi-random variation in voltage improvements, which we exploit for our analysis. The contractor selected 76 locations for transformer injection ('treatment sites'), but many more sites could have been selected. Using spatial data covering the entire electricity network in Accra, our research team identified other segments of the LV grid that were between 200 and 300 meters from both any existing transformers and any treatment locations—thus following the main criterion for treatment site selection—and then randomly selected 75 locations from this set ('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 for data collection in each site ([Figure A6](#) presents an example). We first identify segments of LV lines that are <200 meters from the new or placebo transformer location and >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.

5.2 Data

We began collecting voltage quality and reliability data in March 2018 with all 151 sites covered 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 A9](#) presents a timeline).

Baseline surveys with 6-7 firms and 6-7 households in each site were conducted in March–April 2021 and endline surveys in July–September 2022.¹⁷ As discussed in [Subsection 4.2](#), there is no overlap between survey respondents and respondents that received a GridWatch device.

Of 2,001 respondents surveyed at baseline, 1,575 were surveyed at the endline one year later. Attrited respondents are similar to non-attrited respondents along most socioeconomic characteristics, though they differ along certain variables commonly associated with attrition such as age, household size, and rental status ([Table C1](#)). Importantly, there are no socioeconomic differences between attrited respondents in treatment and control locations with the exception that respondents that attrited from treatment locations were less likely to own their premises ([Table C2](#)).

To verify compliance with planned transformer injections, we use construction progress reports submitted by the private contractor, tracking each site. We also conducted site visits between

¹⁷Due 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 6](#)). In addition, the short period between construction and baseline surveys is likely to have been too short for households or firms 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 B5](#)).

Table 4: Baseline balance

	Control N	Mean	Treat N	Difference	p-val	Accra Mean
<i>(a) All respondents</i>						
Completed secondary education (=1)	772	0.50	803	-0.00	0.983	
Owns premises (=1)	772	0.37	803	-0.02	0.368	0.59
Any television (TV) at location (=1)	772	0.68	803	-0.05	0.040	0.85
Any fridge at location (=1)	772	0.63	803	0.02	0.434	0.62
Any reliability protective device owned (=1)	772	0.25	803	-0.02	0.461	
Count of reliability protective devices	772	0.35	803	0.01	0.694	
Reported number of outages in past month	772	6.98	803	0.35	0.139	
Reported 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	
Appliance damaged by voltage in past year (=1)	772	0.25	803	-0.04	0.056	
Spending on burnt/broken apps in past year (USD)	768	9.18	794	-0.25	0.877	
<i>(b) Households only</i>						
Last month household income (USD)	347	325.97	367	-5.84	0.864	328
Adults with paid jobs	363	0.64	383	-0.03	0.265	
<i>(c) Businesses only</i>						
Number of workers	409	1.99	420	0.04	0.790	7
Last month business revenue (USD)	343	397.94	380	-0.54	0.990	7188
Last month business profit (USD)	310	102.40	336	8.18	0.457	1851
Usual business open hours	409	12.16	420	0.19	0.268	

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. 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. Summary statistics for the population of businesses in Accra are taken from Ghana Statistical Service data from the 2015 Integrated Business Establishment Survey II. [Table B2](#) presents additional outcomes, joint F-test results, and additional detail. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

November 2020 and October 2021 to confirm the presence (absence) of new transformers at treatment (control) sites. [Subsection 5.5](#) presents robustness to heterogeneity in construction completion.

5.3 Baseline balance between treatment and control sites

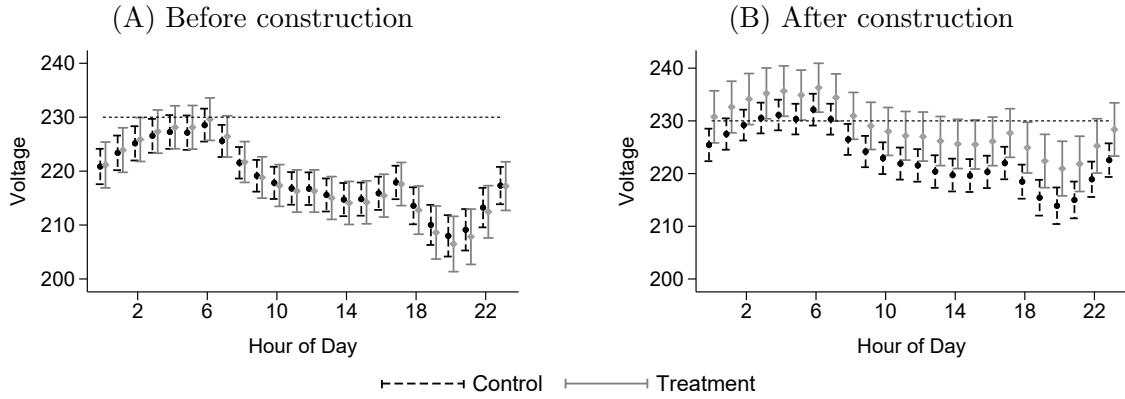
To lend support to the quasi-random nature of the assignment mechanism, we conduct a battery of tests examining baseline differences between control and treatment sites. In line with the site selection procedure described in [Subsection 5.1](#), the distributions of distance between each survey respondent and the nearest existing transformer prior to line bifurcation are statistically indistinguishable across control and treatment sites (Panel A of [Figure A12](#)).¹⁸ [Table 4](#) shows that respondents' socio-economic characteristics at baseline are balanced across treatment and control sites ([Table B2](#) presents additional outcomes).¹⁹

Levels and pre-trends in outages and voltage by site treatment status are statistically indistinguishable before the line bifurcation intervention across a host of outcomes. Panel A of [Figure 4](#) shows that treatment and control sites have indistinguishable voltage patterns across all hours of the day in the pre-period. [Figure 6](#) shows parallel pre-trends for average voltage and outages in the 18 months leading up to the intervention ([Figure A10](#) shows parallel pre-trends for absolute voltage

¹⁸Prior to construction, respondents at control (treatment) sites are on average 233 (253) meters from the nearest transformer (see [Figure A12](#) for the full distribution).

¹⁹The p-value for a joint F-test for household characteristics is 0.230, while that for firm characteristics is 0.407.

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 C3](#) shows impacts on outage duration.

deviation, standard deviation, hours of spells $>10\%$ below nominal, and hours of spells $>20\%$ below nominal). Panels A and C of [Figure 5](#) show that the *distribution* of voltage quality across sites was also similar across treatment and control sites prior to the intervention. Monthly nighttime radiance data, a reasonable proxy for power outages, show nearly identical levels and trends for up to 10 years prior to the intervention ([Figure A11](#)).

Taken together, the evidence of baseline balance and parallel pre-trends, in conjunction with the quasi-random institutional design of the line bifurcation investments, supports the logic that a difference-in-differences design will identify the causal impacts of these electricity grid improvements.

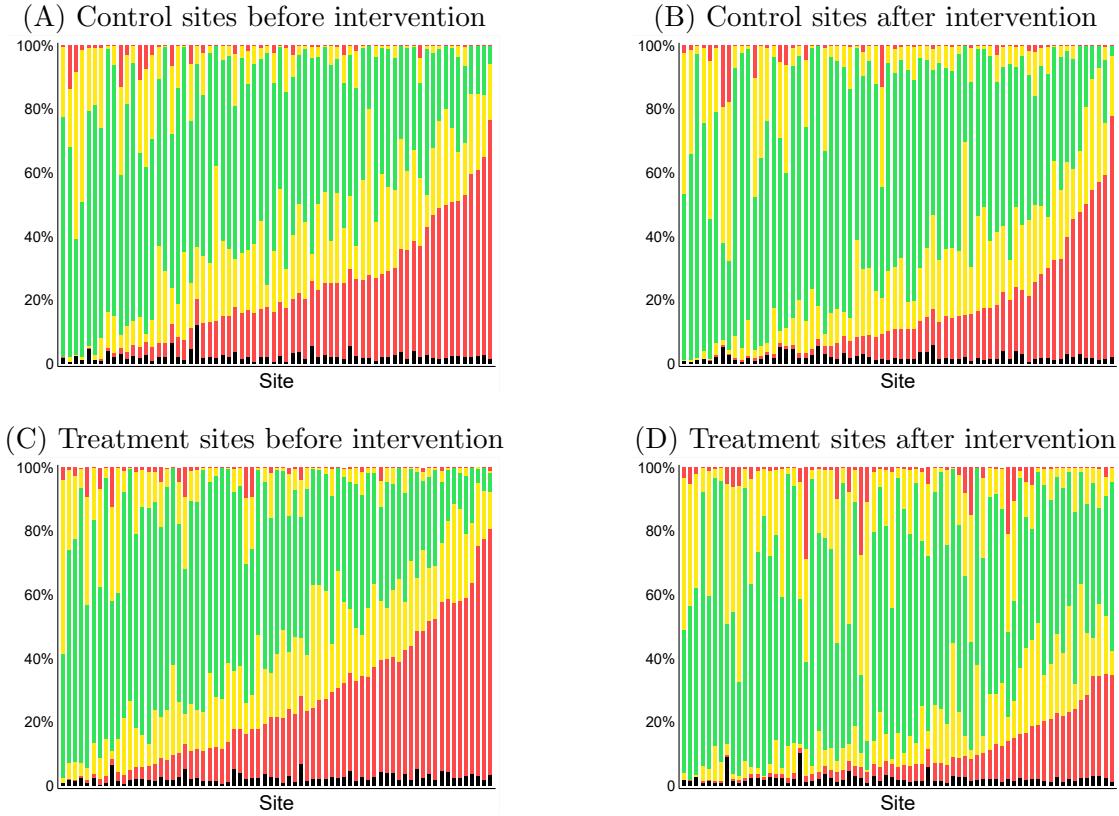
5.4 Results: Impact of line bifurcation on power quality

[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 $\pm 5\%$ of nominal voltage across all hours.

[Figure 5](#) visualizes the impact of the new transformers by comparing voltage before and after the intervention across control and treatment sites. For each site, it shows the fraction of time the minute-by-minute data are within different voltage ranges. Green areas indicate the fraction of time electricity fell within $\pm 5\%$ of nominal voltage. 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, or between 5-10% below nominal. It also increased the amount of time

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 $\pm 5\%$ of nominal voltage. Yellow areas indicate $\pm 5\text{-}10\%$ while red areas indicate a greater than $\pm 10\%$ deviation from nominal voltage.

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 under-voltage spells, which are most likely to damage appliances and affect use.

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

$$Y_{ist} = \beta_0 + \beta_1 \text{Post}_t + \beta_2 \text{During}_t + \beta_3 \text{Treat}_s \times \text{Post}_t + \beta_4 \text{Treat}_s \times \text{During}_t + \boldsymbol{\Gamma}_s + \boldsymbol{\Gamma}_t + \epsilon_{ist} \quad (1)$$

Y_{ist} is an outcome experienced by device i in site s at time $t \in \{0, 1\}$. $\boldsymbol{\Gamma}_s$ are site fixed effects, which subsume a Treat dummy. $\boldsymbol{\Gamma}_t$ are time fixed effects that vary across regressions.²⁰ We include a ‘During’ dummy to capture direct effects of construction itself: during this period, temporary influences such as the disconnection of the grid to be able to conduct wiring or the connection of construction machinery could have direct effects. β_1 and β_2 capture changes in overall voltage quality or outages after and during construction relative to the pre-construction period. β_3 captures

²⁰Results 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)	(2)	(3)	(4)	(5)	(6)
	Minutes power out	Average voltage	Absolute voltage deviation	Standard deviation voltage	Hours of spells >10% below nominal	Hours of spells >20% below nominal
During construction	0.21*** (0.07)	0.76 (1.09)	-0.67 (1.19)	0.10* (0.05)	1.13 (10.50)	0.93 (9.37)
Treat X During	-0.06 (0.12)	2.38 (1.60)	-1.47 (1.54)	-0.27** (0.11)	-38.49** (17.57)	-34.37** (15.08)
Post	-0.08 (0.08)	5.94*** (1.74)	-3.74*** (1.14)	-0.18 (0.11)	-43.46*** (14.11)	-32.03*** (11.31)
Treat X Post	-0.21 (0.13)	5.48** (2.48)	-0.83 (1.70)	-0.51*** (0.14)	-54.68*** (20.80)	-41.99** (16.82)
Observations	10033086	9866078	9866078	9831794	14213	14213
Pre-constr. ctl. mean	1.39	219.18	16.51	2.49	125.07	76.69
Hour of day FE	Y	Y	Y	Y	N	N
Week of year FE	Y	Y	Y	Y	N	N
Month of year FE	N	N	N	N	Y	Y
Site FE	Y	Y	Y	Y	Y	Y
Hourly/monthly data	Hourly	Hourly	Hourly	Hourly	Monthly	Monthly

Difference-in-difference results for the impact of treatment on power quality measured by GridWatch devices, with each column a different outcome variable. Columns (1)-(4) use hourly data while Columns (5)-(6) use monthly data. Standard errors are clustered at the site level. [Figure 6](#) and [Figure A10](#) shows event study graphs for each outcome variable. [Table C3](#), [Table C4](#), [Table C5](#) and [Table C6](#) show additional outcomes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

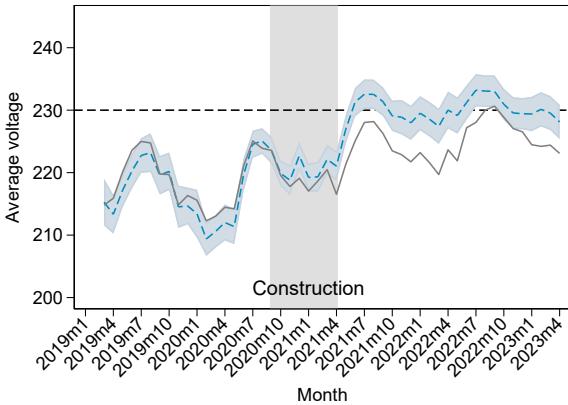
the average treatment effect of interest. Standard errors are clustered by site in all regressions.

[Table 5](#) presents the results. Columns (1)-(4) use hourly data to estimate the impact of line bifurcation on four metrics of power quality: minutes of power outages, average voltage, the absolute voltage deviation from nominal voltage, and the standard deviation of voltage.²¹ The transformer injection intervention increased average voltage by 5.5V relative to control sites, but had no impact on power outages. The pre-construction average voltage was 219V, and the post-construction average rose to approximately 225V in control sites and 230V in treatment sites. The average absolute voltage deviation in a given minute did not change in treatment sites relative to control sites, likely because of increased small deviations above nominal in treatment sites. In addition to improving average voltage, line bifurcation improved the minute-by-minute variation in voltage. Column (4) indicates that after the intervention, the standard deviation of voltage decreased by 0.51 in treatment sites relative to control sites. Columns (5) and (6) 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). The treatment caused a 55 (42) hour decrease in the monthly hours of spells with voltage more than 10% (20%) below nominal, respectively—a 44% (55%) decrease.

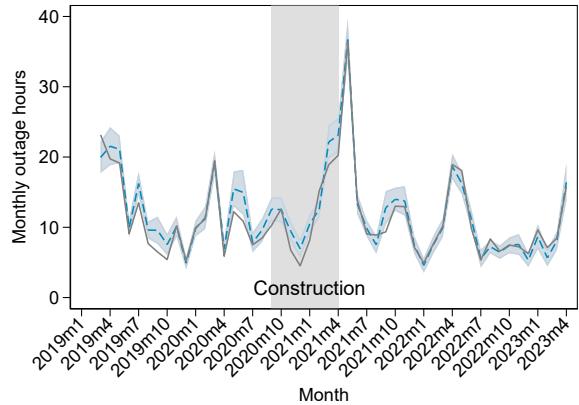
The number of low-voltage spells per month, defined as periods when the voltage fell at least 10% below nominal, fell by 68 in treatment sites relative to control sites, a 27% decrease relative to

²¹Results are similar in alternative specifications considering ways in which transformer injection implementation deviated from initial plans ([Table C3](#), [Table C4](#)).

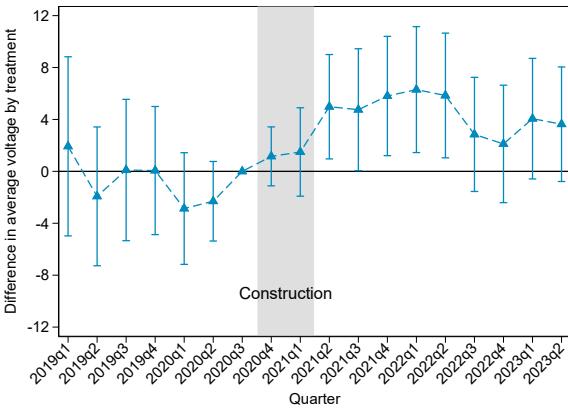
Figure 6: Impacts of transformer injection intervention on power quality and reliability
 A) Average voltage, monthly means



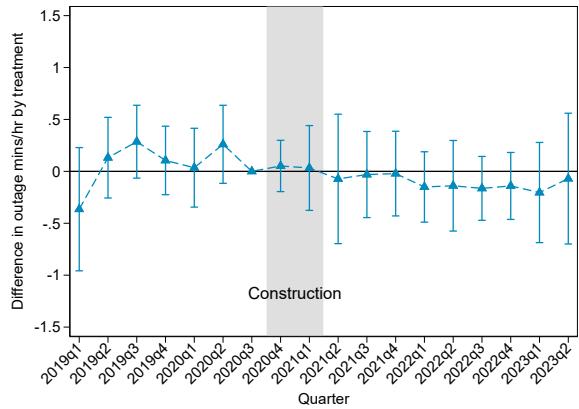
B) Monthly outage hours, monthly means



C) Treatment effect on hourly average voltage



D) Treatment effect on hourly outage minutes



— Control - - - Treatment

Panels A and B show monthly mean values by treatment with 95% confidence intervals for treatment means. 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 A10](#) shows results for absolute voltage deviation, standard deviation, hours of spells >10% below nominal, and hours of spells >20\$ below nominal. Treatment coefficients use $t = -1$ as the reference period and thus do not exactly match those presented in [Table 5](#), which use the entire pre-period as the reference period. [Figure C6](#) shows Panels (C) and (D) but dropping the 25 percent of control sites that saw the most significant improvements in voltage quality.

the pre-construction control mean. Spells where the voltage drops >20% below nominal decreased by 4.6, or 50% ([Table C6](#)). Remaining spells are not shorter on average in treatment sites, though the maximum monthly spell length is 5.9 hours (50%) shorter after construction relative to control sites. Despite the reduction in low-voltage hours and spells, customers at treatment sites remain vulnerable to severe spells after construction. Mean voltage during low-voltage spells is 16V lower in treatment sites relative to control sites, indicating the remaining spells are likely caused by issues other than load fluctuations on the local grid.

[Figure 6](#) presents event study results showing the impact of line bifurcation on average voltage and outage hours by quarter. Hourly average voltage increases during and post-construction, while line-bifurcation has no impact on outages. Voltage gains at treatment sites relative to control sites

were stable for a year after construction completion, but decreased slightly and were no longer significant after around 18 months (Panel C). The increases in average voltage are not significantly different for devices in treatment sites at different distances from the nearest transformer at baseline ([Figure C4](#)).

[Figure 4](#), [Table 5](#), [Figure 5](#), and [Figure 6](#) Panel A also show voltage quality improvements over the study period at control sites (the causal voltage improvement at treatment sites is on top of this improvement at control sites). Broad-scale voltage improvements may be attributable to three factors. First, voltage improvement at control sites may be attributable to spillover effects from treatment sites, given the physics of power flow across the distribution grid. However, empirical tests indicate that this is likely not the case. The voltage improvement at control sites does not differ significantly by distance to the nearest treatment site ([Table B4](#)), which one would expect if these improvements were due to reduced load in nearby connected portions of the grid. Furthermore, line bifurcation did not significantly change distances to the nearest transformer in control sites (Panel B of [Figure A12](#)), 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.

Second, macroeconomic conditions related to the COVID-19 pandemic might have reduced residential load, contributing to generally improved power quality. However, power quality does not change noticeably with the onset of COVID-19 in 2020, with similar seasonal patterns in average voltage going back to when the first GridWatch devices were deployed in 2018. COVID-19 electricity subsidies in Ghana may have helped to maintain electricity consumption levels despite economic difficulties in this period (Berkouwer et al., [2022](#)). Further, data on electricity spending by survey respondents indicates similar consumption at baseline and endline, indicating changes in voltage quality are not due to changes in electricity loads in the study areas.

Third, and more likely, the broad-scale voltage improvements result from other large-scale concurrent investments that the MCC made in the grid as part of its Ghana Power Compact. The construction of additional primary substations and bulk supply points will have improved the operations of the grid as a whole (MCC, [2014](#)). We return to the discussion of broad-scale voltage improvements, including at control sites, when interpreting the results on customer outcomes below.

5.5 Results: Impact on customer outcomes

We estimate impacts of the line bifurcation treatment on customer outcomes using the following difference-in-differences specification:²²

$$Y_{ist} = \beta_0 + \beta_1 \text{Post}_t + \beta_2 \text{Treat}_s + \beta_3 \text{Treat}_s \times \text{Post}_t + \mathbf{X}_i + \epsilon_{ist}, \quad (2)$$

²²This 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. Results for all outcomes listed in the pre-analysis plan are included in [Appendix D](#).

For outcome Y_{it} experienced by respondent i at site s at time $t \in \{0, 1\}$. β_3 captures the differential outcome being observed post-construction in treatment sites—the treatment effect of interest. \mathbf{X}_i are baseline socioeconomic controls.²³ Standard errors are clustered by site in all regressions.

Despite a first-stage where voltage quality improves in treatment sites relative to control sites, we find limited effects of the treatment on outcomes for households and small firms. [Figure 7](#) presents the results for impacts on outcomes related to customer electricity experiences, normalized around the baseline control mean, pooled for firms and households ([Table B5](#) provides detail).²⁴ 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—corresponding to a 20% decrease in voltage-related damages. Monthly WTP for an electricity connection with perfect reliability and half the current bad voltage hours increases by USD 1 in treatment relative to control sites. WTP for other improved electricity connections does not change significantly. There are no significant impacts on any other electricity-related outcomes. We also find no impact on a variety of firm and household outcomes, as shown in [Figure 7](#).²⁵

The improved power quality in control sites stemming from broad-scale electricity grid investments is reflected in significant estimated average differences between baseline and endline electricity outcomes ([Table B5](#)). By the endline period, all sites saw declines in the probability of having had an appliance damaged by voltage issues over the past 12 months, spending on damaged appliances, ownership of voltage protective devices, reported hours of outages and bad voltage, and WTP for improved electricity connections. Self-reported daily hours of bad voltage were nearly zero during the endline even at control sites. Seventy-one percent of respondents at endline said voltage was much better than two years ago (19% said it was slightly better), and firms were 19 percentage points less likely to report bad voltage as an obstacle to firm operations at endline compared to baseline. Improvements in reported electricity outcomes across the whole sample may also have been due to seasonal differences in energy use and economic activity due to the differences in the timing of the two surveys: voltage is typically better in July-September, which coincides with the endline survey (Panel A of [Figure 6](#)).

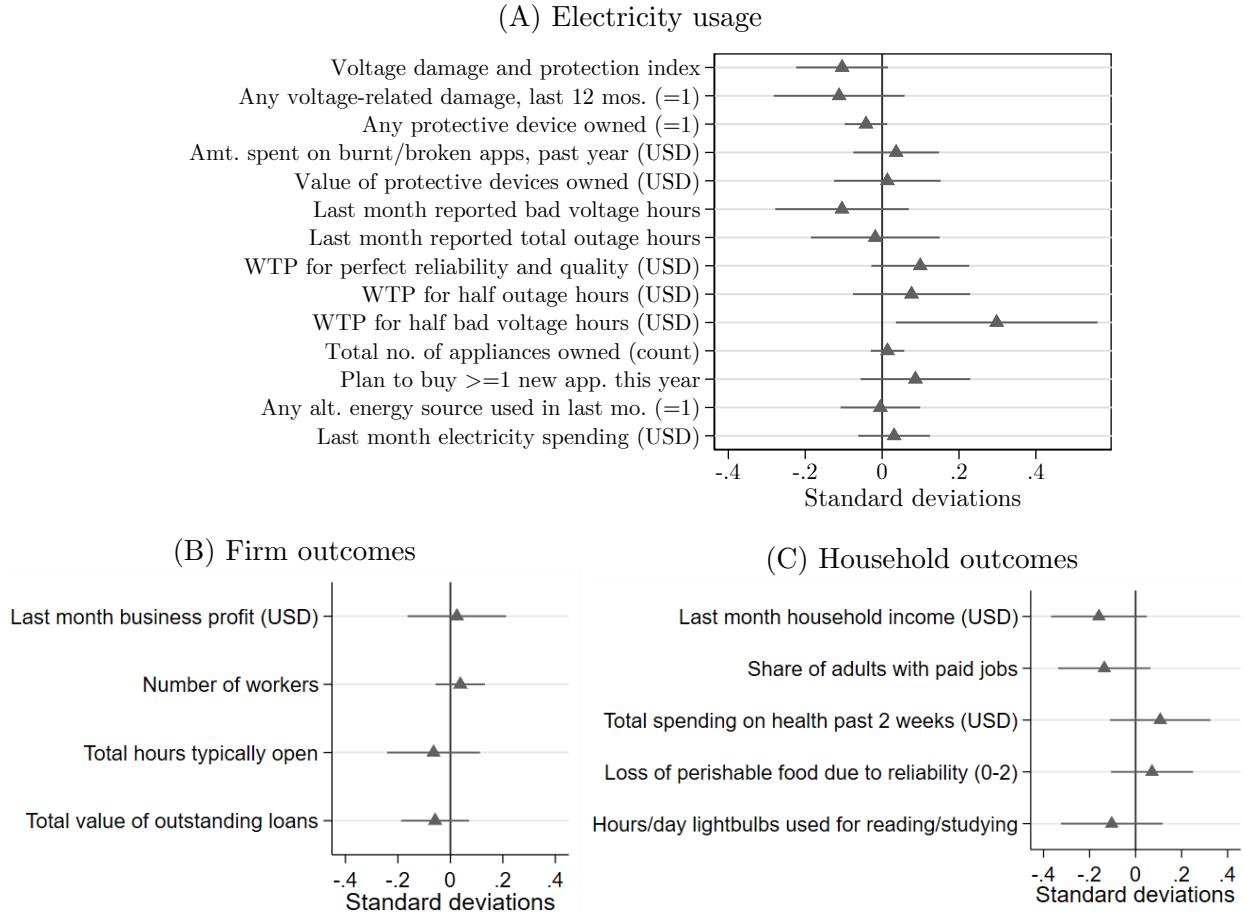
Our findings of null treatment effects on most customer outcomes are robust to a variety of potential sources of bias ([Appendix C](#)). There is no evidence of treatment spillovers ([Table B4](#)). Still, to address potential SUTVA violations due to any potential treatment spillovers, we drop control sites closer to treatment sites than median (1.3km). We also drop ‘movers’ and anyone for whom the monotonicity assumption on distance to the nearest transformer is violated ([Table C9](#)). These changes to the sample do not change the results. We next consider differences across treatment sites

²³ Age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is a household or a firm, baseline distance to the nearest transformer, and district fixed effects.

²⁴ [Table C7](#) shows outcomes for firms alone; the pattern of results is similar.

²⁵ We find significant decreases in firm costs in treatment sites of a similar magnitude to non-significant decreases in revenues, both of which offset significant increases in control sites ([Table B6](#)), suggesting treatment firms did not grow as much as control firms. These effects do not survive adjustments for multiple hypothesis testing ([Table C8](#)). We find no significant effects on a number of additional household outcomes ([Table B7](#)).

Figure 7: Impact of transformer injection treatment on primary outcomes



Coefficients and 95% confidence intervals for β_3 ($Treat_s \times Post_t$) from [Equation 2](#). All units are standard deviations relative to the baseline control mean. Panel A pools firm and household respondents. The voltage damage and protection index is comprised of ‘any voltage-related damage’ and ‘any protective device owned’. [Table B5](#) shows the results for non-normalized versions of these and additional outcomes related to electricity. [Table B6](#), and [Table B7](#) show results for non-normalized versions of the outcomes in for firms in panel B and households in panel C, respectively, along with additional firm and household outcomes.

in where and when planned transformer construction was completed, drawing on contractor reports and our own monitoring visits ([Table C3](#), [Table C4](#), and [Table C9](#)).²⁶ Increases in average voltage and decreases in voltage damages are slightly larger in sites where in-person visits confirmed the presence of new transformers in treatment sites. However, we cannot reject equality of coefficients, and even in sites with confirmed transformer injections we find null effects on most socioeconomic outcomes.

²⁶We 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.

5.6 Discussion: Mechanism underlying economic impacts

These findings raise the question: why do voltage improvements not translate into more substantial economic impacts on customers? Voltage quality improved significantly in treatment sites relative to control sites. Voltage instability is a clear concern for consumers, leading to appliance damage and a willingness to pay for better power quality, as shown in [Subsection 4.1](#). Despite this, we observe minimal socioeconomic effects in the medium term. We consider several possible explanations.

5.6.1 Heterogeneous treatment effects by voltage improvement?

One possibility is that the results reflect non-linear impacts of voltage improvements—where marginal effects diminish at higher voltage levels—or simply that the treatment’s economic effect was too small to be statistically detectable.

To assess this, we first consider treatment effect heterogeneity by baseline voltage quality. We categorize a site by whether it was above or below the median daily hours of voltage that was within 10% of nominal. Sites with below median voltage (averaging 210V at baseline) experienced at endline an average of 220V at the control sites and 229V at the treatment sites ([Table B8](#)). In contrast, sites with above median voltage (averaging 228V) saw small and statistically insignificant increases in average voltage at endline. Given these differences across sites, if impacts are non-linear, we would expect estimated treatment effects to be larger in the sites with below median voltage at baseline. However, we see limited difference in treatment effects on economic outcomes across the two samples. Even among sites with below-median voltage at baseline, the socioeconomic impacts remain largely statistically insignificant ([Table B9](#) Column 1).

A second approach is to remove control sites that experienced large increases in voltage between baseline and endline from the sample. We restrict the sample of control sites to those that experienced less than 10 V of improvement in average voltage after line-bifurcation, which is the 75th percentile of voltage improvement in the control sites. The remaining control sites and treatment sites are balanced in terms of observable characteristics at baseline ([Table C11](#)). This increases the difference between treatment and control sites to more than 10 V ([Figure C6](#), [Table C12](#)). Still, even among this subsample, the estimated effects on firm and household outcomes are largely unchanged ([Table C13](#), [Table C14](#)). While we interpret these results with caution because the sample is not randomly assigned, they indicate that a larger increase in voltage in treatment sites may not have caused larger socioeconomic impacts.

5.6.2 Heterogeneous treatment effects by respondent characteristics?

The areas targeted for the line bifurcation investments did not include many wealthy households or large businesses, who may have experienced larger treatment effects. While we cannot directly test whether economic impacts would have been larger for such customers, we test for differences within our sample by baseline characteristics that reflect the importance of voltage quality for respondents, including reported electricity importance (for firms), willingness to pay for perfect

electricity reliability and quality, ownership of protective devices, general appliance ownership, and fridge ownership. In general we find no significant differences ([Table B9](#) Columns 3–7).

We also identify a set of respondents that may be the most susceptible to voltage issues: those who experienced below median voltage at baseline and at the same time owned appliances sensitive to voltage but no protective devices. They comprise only 14% of the sample, and we refer to them as those with the “worst” baseline conditions. However, we still find no differences in the effects of the treatment on these respondents relative to others ([Table B9](#) Column 8).

5.6.3 Inertia in appliance adoption and potential for longer-term impacts

Low-quality electricity may cause customers to purchase a limited stock of electric appliances, and treatment effects may only be realized in the longer term, as customers improve or expand their stock. The economic gains from voltage improvements would then depend on capital investments in new appliances and machinery, which may not occur within 16 months of the intervention. Ghana has faced over a decade of unreliable electricity supply, marked by both outages and low voltage, with intermittent periods of improvement. In such an environment, households may delay capital investments in appliances until improvements in power quality are perceived as more permanent. The economic disruption caused by the COVID-19 pandemic may have further suppressed household investment in appliances during this period.

We find no evidence that treatment households increased appliance adoption in the near-term. At baseline the median respondent owned 3 different types of electric appliances along with light bulbs. We observe no difference in appliance acquisition after line bifurcation by treatment status: 37% of respondents at endline in both treatment and control sites reported acquiring at least one new appliance since the baseline survey, with no difference between firms and households ([Figure A13](#)). Many of these new appliances replaced old ones, such that the mean total count of electric appliances did not change significantly between baseline and endline.

However, there is suggestive evidence that customers in treatment sites were more likely to purchase additional appliances after the improvement in voltage. Fifty-six percent of the sample at both baseline and endline report plans to purchase at least one new appliance in the next year. Customers in treatment sites are 4.3 percentage points (7.4%) more likely to state they plan to purchase a new appliance, but this effect is statistically imprecise ([Figure 7](#); $p = 0.232$).

Inertia in customers’ investment decisions may be an important explanation for the lack of socioeconomic impacts of line-bifurcation. Utilities implementing grid improvements to enhance voltage quality should therefore expect that any associated economic benefits may take time to emerge. MCC spent \$13.9 million on low voltage line bifurcation in the Achimota, Dansoman, and Kanesie districts of Accra, which had an estimated combined population of around 49,000 households ([GSS, 2014](#)), or \$286 per household. On the one hand, taking the socioeconomic impact estimates at face value, the benefit in terms of avoided investment in voltage protective devices is \$14 and annual repairs and replacements of broken appliances is \$11. Eliminating all protective devices and 100% of damage repair/replacement expenditures every year for 30 years

(discounting at $\delta = 0.9$) for all 49,000 households yields benefits of \$11.6 million, still falling short of the investment cost. On the other hand, these impact estimates could be a significant under-estimate if additional socioeconomic impacts emerge in the longer terms. These back-of-the-envelope calculations furthermore do not include benefits to firm customers and to the electricity utility through reduced technical losses and maintenance costs.

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 firms. We analyze 337 million temporally and spatially high-frequency power quality measurements, as well as panel surveys with 2,000 households and firms, to generate some of the first evidence on the large-scale economic impacts of voltage quality problems.

Poor voltage quality is a pervasive problem: average voltage is 219V—well below nominal voltage of 230V—and is more than 10% below nominal over 20% of the time. These issues create real economic costs for customers in terms of appliance damages and interference with firm operations. Households and firms are willing to pay similar amounts for electricity connections with reduced outages and with improved voltage, indicating that electricity quality imposes similar costs on customers as electricity reliability.

An intervention that added transformers to the grid increased average voltage by 5.5V and modestly reduced voltage-related damages and ownership of protective devices. However, the investment had no impact on household and firm outcomes such as electricity spending, appliance ownership, firm profits, and household income. There are no significant differences in treatment effects across different subgroups, even those that ex-ante are more likely to be impacted by an improvement in voltage quality though the sample does not include larger businesses and wealthy households, who may have greater dependence on electricity.

The null economic effects are not caused by the overall improvement in voltage quality that affected some control sites: even a larger voltage quality improvement has little economic impact. The lack of economic effects despite results highlighting the self-reported importance of power quality to customers may partly be due to customers' investment inertia. Treatment effects may be realized in the longer term as perceptions of improved voltage translates into greater appliance ownership and use. Despite potential longer-term benefits, governments may prefer to invest in other publicly-provided goods, or to identify more cost-effective ways to improve voltage quality.

These results present novel evidence on the economic costs of voltage quality, while at the same time highlighting the difficulty of achieving meaningful economic gains through voltage improvement. We offer a framework with which to evaluate voltage quality 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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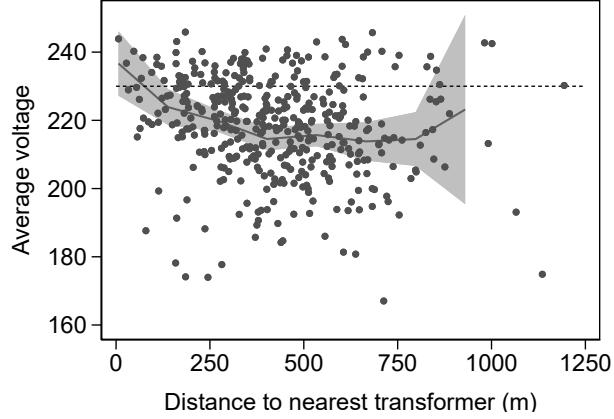
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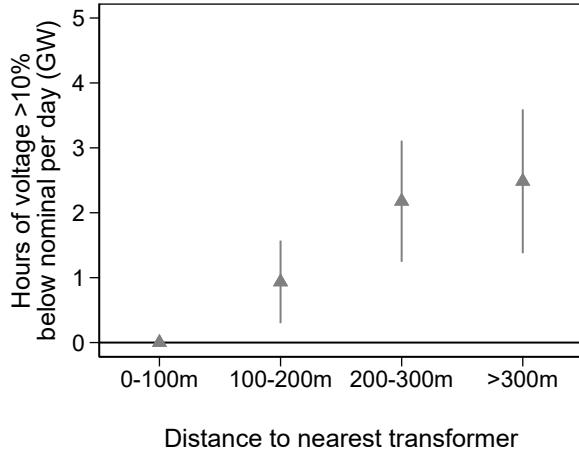
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A Appendix Figures

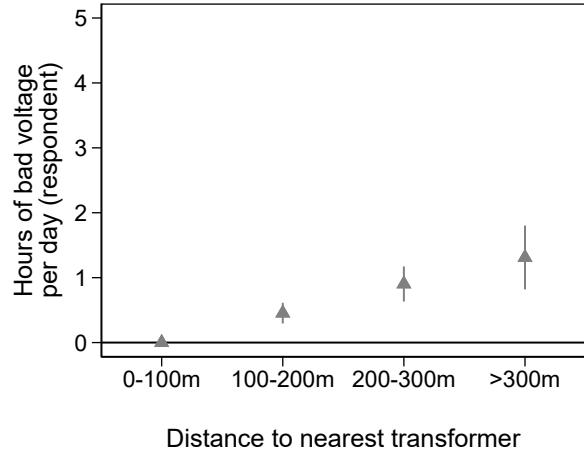
Figure A1: Correlation between average voltage and distance to nearest transformer
 Panel (A) Raw correlation with GridWatch devices



Panel (B) GridWatch devices

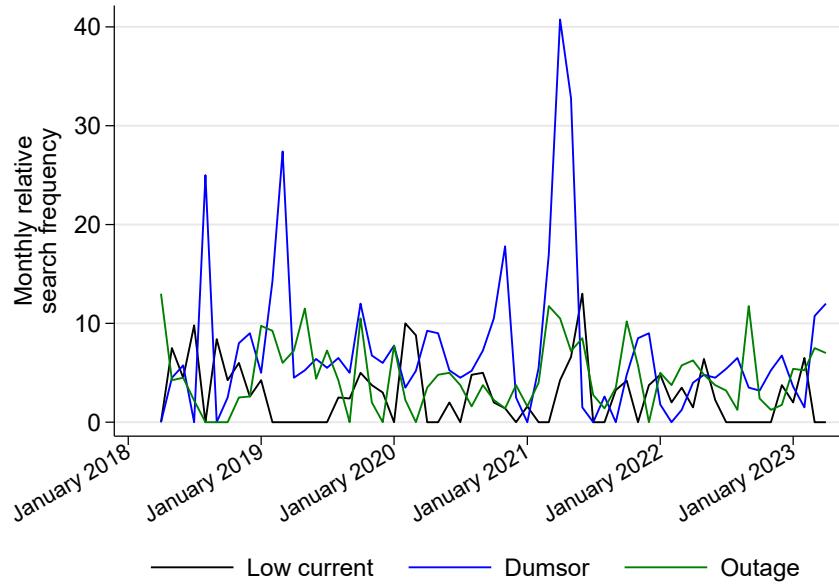


Panel (C) Self-reported



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 over the 30 days preceding the survey.

Figure A2: Google trends for search on voltage and outage issues in Ghana, April 2018-2023



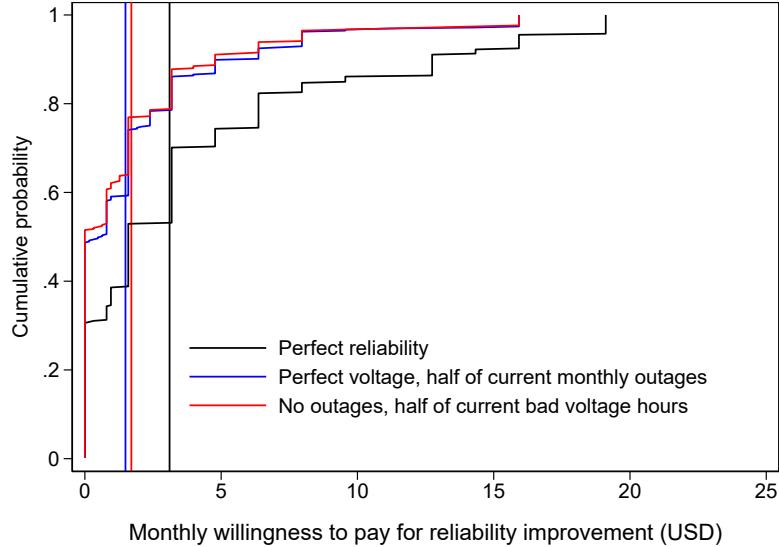
Data are aggregated from weekly Google Trends data for the specified search terms. Relative search frequency is calibrated to the maximum search interest across the three terms over the time period. “Low current” is the most common phrase used in Ghana to refer to issues related to voltage. “Dumsor”, 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 A3: A GridWatch device



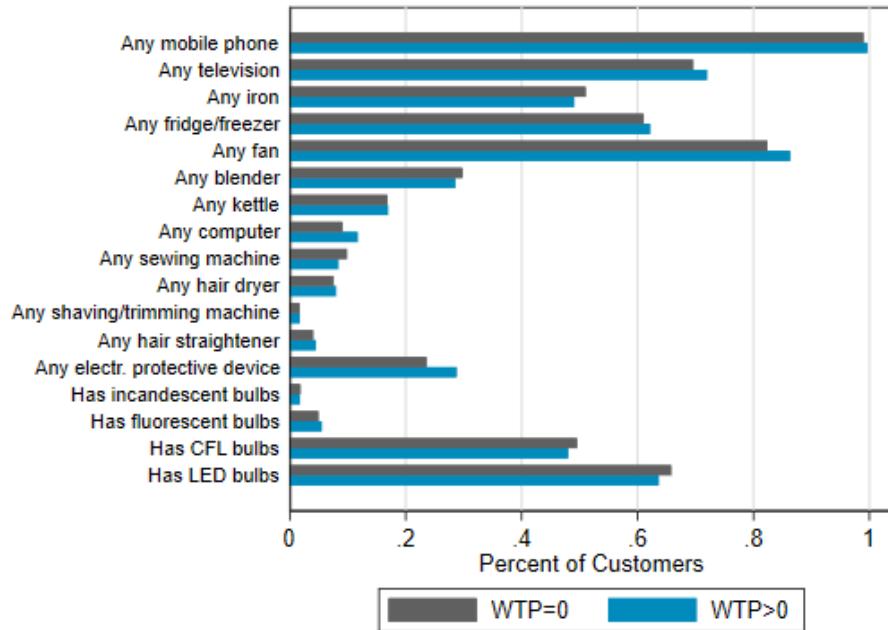
A GridWatch device, part of nLine’s GridWatch technologies used to measure power outages and voltage. Each GridWatch device measures voltage in real-time, stores this on a local SD card, and sends the data to the cloud via a sim card whenever local cellular service permits. A back-end computing technology 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 A4: Willingness to pay for electricity connections with particular characteristics



Willingness to pay is elicited as the maximum monthly amount respondents would be willing to pay for an improved electricity connection, in addition to the cost of their electricity consumption. Respondents are asked first about a connection with perfectly reliable electricity and then elicited about 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 A5: Appliance ownership by willingness to pay for voltage improvements



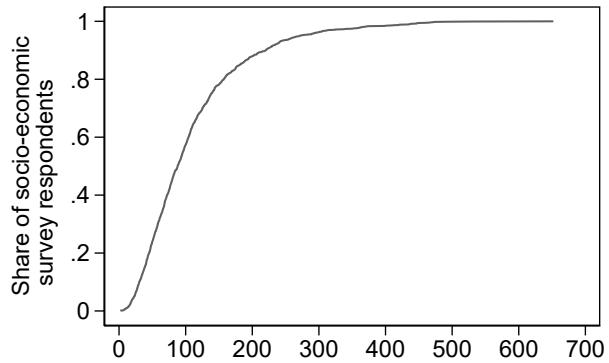
Appliance ownership is at the time of the baseline survey. Willingness to pay is for a connection with half of current outage hours but perfect voltage quality. Results are similar using WTP for a connection with half of current bad voltage hours but no outages.

Figure A6: Example site (230)



A sample site map where field officers conducted surveying. The site centroid is where the transformer is injected at treatment sites. The surveying area (outlined in white) is generated by following the LV lines for up to 200 meters from the centroid and then including any area that is within 50 meters of a line segment. [Figure C1](#) provides more screenshots of example sites.

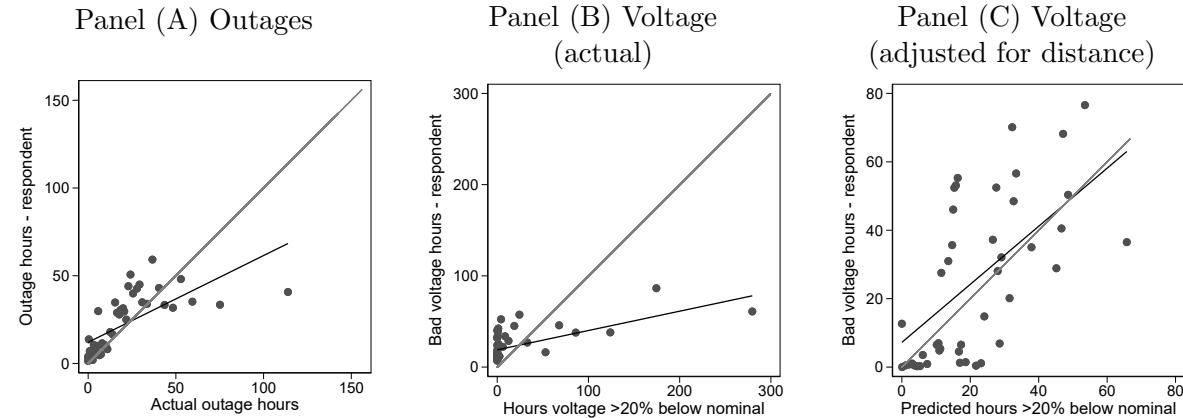
Figure A7: CDF of distances



Distance to matched GridWatch device (meters)

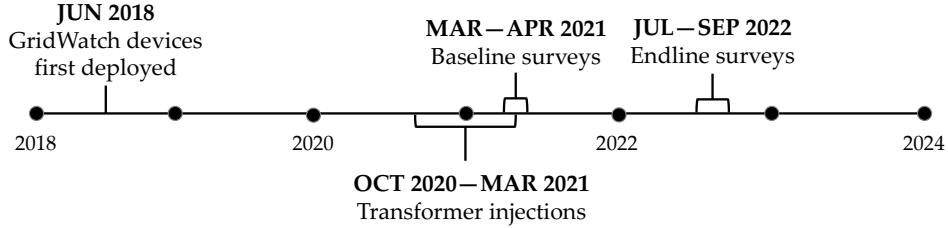
Distribution of distances from each survey respondent to the device whose data they are matched to. The median distance is 88 meters. 80% of the respondents are within 157 meters of their matched device.

Figure A8: Correlations between measured and reported electricity characteristics



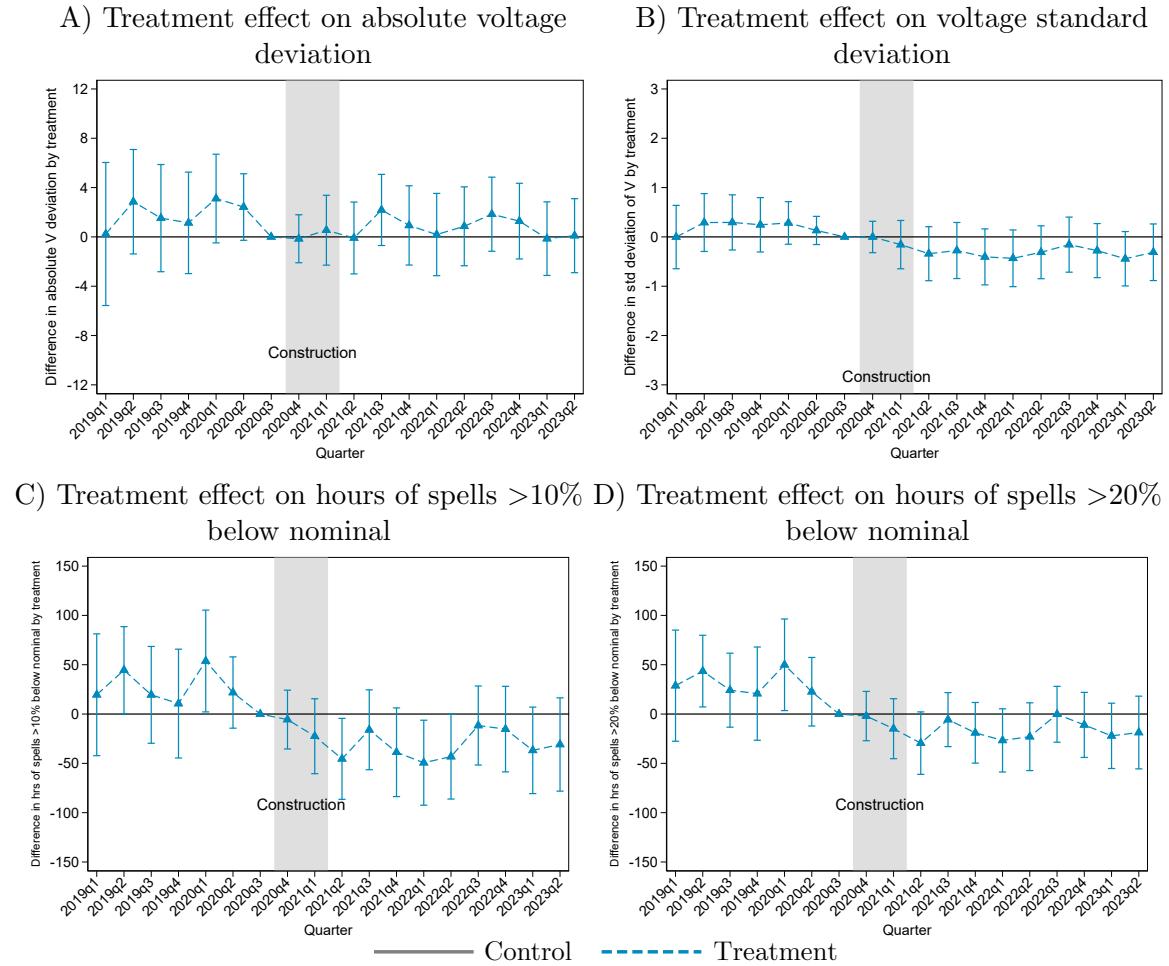
Respondents are matched with data from the device that is nearest to their location (horizontal axes). Predicted hours of bad voltage (panel C) are calculated by adjusting data by respondent and device distance to the nearest transformer. Observations are binned into 50 quantiles of approximately 62 observations each.

Figure A9: Project timeline



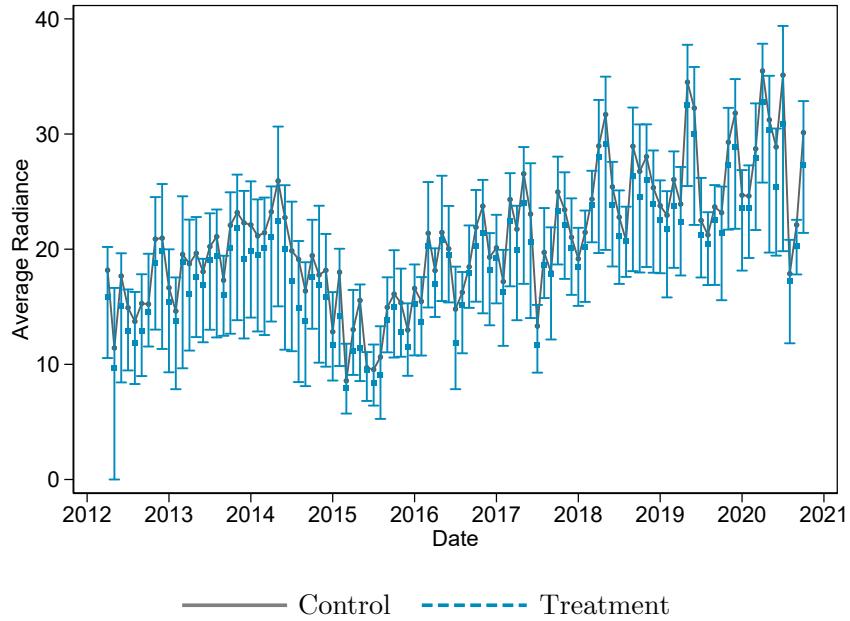
Timeline of research and construction activities. GridWatch data were collected continuously in the months after device deployment. The analyses in this paper include GridWatch data collected through April 2023.

Figure A10: Impacts of transformer injection intervention on power quality and reliability



All panels show estimated coefficients and 95% confidence intervals from a regression of outcomes on site treatment status by quarter. Panels (A) and (B) are estimated using hourly data, controlling for hour of day, week of year, and site fixed effects. In Panel (A), absolute voltage deviation is the absolute value of the hourly voltage deviation from nominal voltage (230 V). Panels (C) and (D) are estimated using monthly data, controlling for month and site fixed effects. SEs clustered by site. Treatment coefficients use $t = -1$ as the reference period and thus do not exactly match those presented in [Table 5](#), which use the entire pre-period as the reference period.

Figure A11: Balance in nightlight radiance

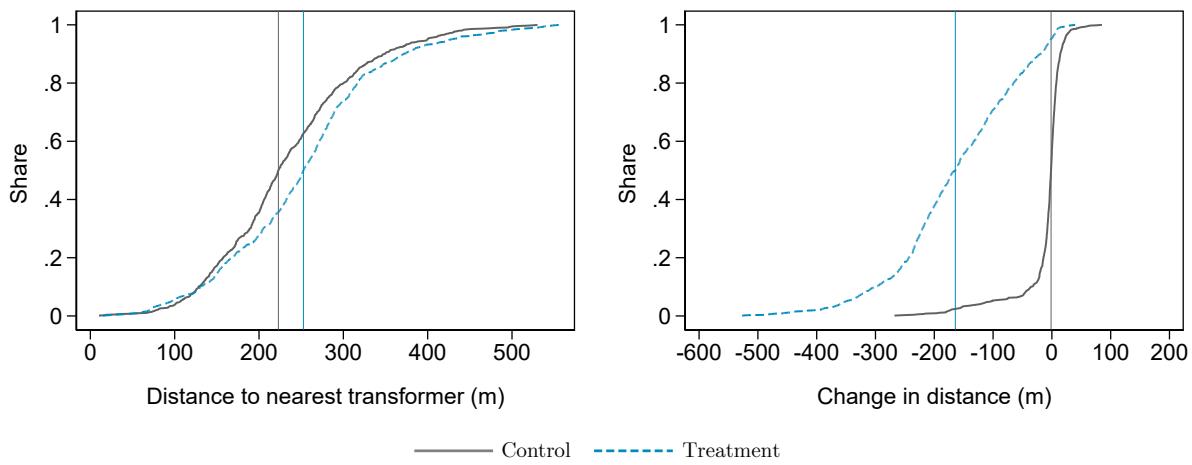


Median monthly nighttime Visible Infrared Imaging Radiometer Suite (VIIRS) radiance between 2012-2020 per site-month, with bands showing the 25th to 75th percentile (Elvidge et al., 2017).

Figure A12: Distance between each respondent and their nearest transformer

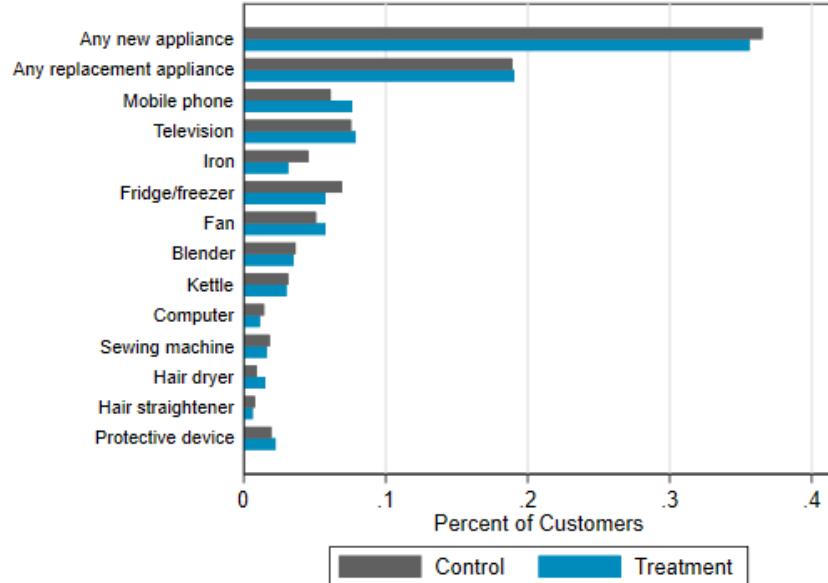
(A) Before construction

(B) Change from before to after construction



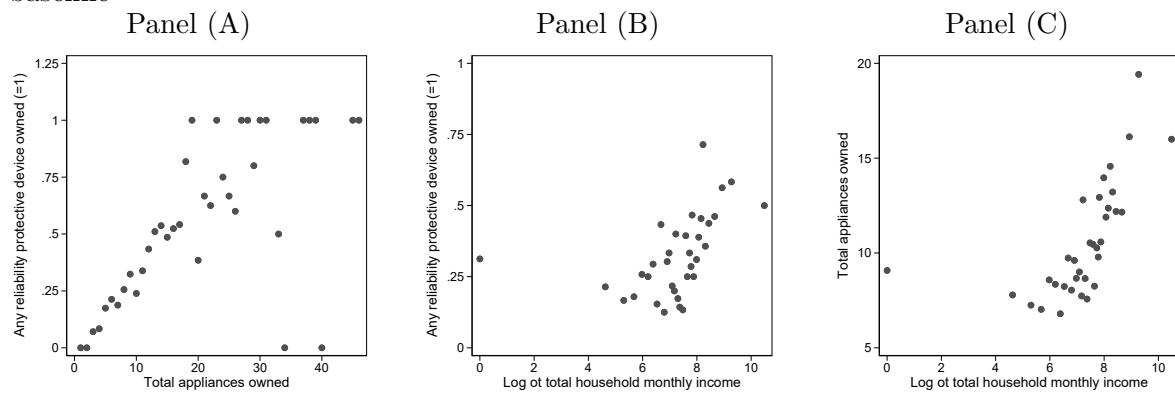
Panel A shows the distance (in meters) from each respondent to the nearest transformer at baseline for survey respondents. Panel B shows the change in this distance from baseline to endline. The figures includes a small number of individuals who moved within the survey sites between baseline and endline, which accounts for nearly all the variation in distances to transformer in control sites. Vertical lines mark the median respondents in control and treatment sites.

Figure A13: Appliance acquisition between surveys by site treatment status



Shares of respondents (pooling business and household respondents) who report acquiring that appliance between baseline and endline, across treatment and control sites.

Figure A14: Correlations between appliance ownership, protective device ownership, and income at baseline



B Appendix Tables

Table B1: Baseline correlates of power quality and reliability

	N	Mean (SD)	Monthly hours > 10% below nominal	Monthly outage hours
Distance to nearest transformer (10m)	1566	24.24 (9.15)	2.17** (0.84)	0.34** (0.17)
Shares electricity meter with other users (=1)	1566	0.40 (0.49)	-0.69 (7.92)	-1.53 (1.70)
Wealth index (normalized)	1566	-0.14 (0.98)	-1.44 (4.83)	-0.37 (1.26)
Household members	741	3.63 (1.91)	1.14 (2.44)	0.45 (0.62)
Monthly household income (USD 100s)	709	3.36 (4.86)	-0.81 (1.13)	-0.04 (0.20)
Number of workers	825	1.95 (1.99)	-1.81 (1.89)	-0.20 (0.29)
Last month business revenue (USD 100s)	719	3.87 (5.68)	-1.37* (0.75)	0.16 (0.16)
Outcome mean			128.0	25.5

The table presents results from 14 regressions, with two baseline measures of power quality from GridWatch devices deployed near survey respondents as the outcome variables (columns) and 7 survey respondent characteristics as the independent variables (rows). Voltage data is not available for respondents in one site where no devices were deployed. 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B2: Baseline balance by site status

	Control N	Control Mean	Treat N	Treat Difference	p-val	Accra Mean
<i>Respondent and Location</i>						
Age (years)	772	38.79	803	-0.85	0.141	45.39
Respondent is male (=1)	772	0.36	803	0.01	0.753	0.67
Completed secondary education (=1)	772	0.50	803	-0.00	0.983	
Owns premises (=1)	772	0.37	803	-0.02	0.368	0.59
<i>Appliances</i>						
Any television (TV) at location (=1)	772	0.68	803	-0.05	0.040	0.85
Any fridge at location (=1)	772	0.63	803	0.02	0.434	0.62
Count of mobiles	772	2.23	803	0.13	0.107	3.02
Any reliability protective device owned (=1)	772	0.25	803	-0.02	0.461	
Count of reliability protective devices	772	0.35	803	0.01	0.694	
<i>Electricity and Energy</i>						
Pays someone else for electricity (=1)	772	0.09	803	0.01	0.611	
Count of meter users	772	1.76	803	-0.11	0.141	
Last month electricity spending (USD)	763	17.59	796	1.78	0.026	5.99
Has generator (=1)	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	
Last month spending on alternative fuels (USD)	772	7.93	803	1.27	0.241	
<i>Reliability</i>						
Reported number of outages in past month	772	6.98	803	0.35	0.139	
Reported 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 (=1)	772	0.25	803	-0.04	0.056	
Amt. spent on burnt/broken apps in past year (USD)	768	9.18	794	-0.25	0.877	
<i>Household Characteristics</i>						
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
Last month HH income (USD)	347	325.97	367	-5.84	0.864	328.25
Share of HH adults (18+) with paid jobs in last 7 days	363	0.64	383	-0.03	0.265	
<i>Business Characteristics</i>						
Number of workers	409	1.99	420	0.04	0.790	7
Last month business revenue (USD)	343	397.94	380	-0.54	0.990	7187.50
Last month business costs (USD)	325	283.14	366	-25.99	0.359	
Last month business profit (USD)	310	102.40	336	8.18	0.457	1851.44
Usual business open hours	409	12.16	420	0.19	0.268	
Any non-electric business machines at location (=1)	409	0.09	420	-0.00	0.905	
Business engaged in retail activities (=1)	409	0.44	420	-0.00	0.933	
Business engaged in manufacturing activities (=1)	409	0.22	420	0.02	0.378	
Business engaged in other service activities (=1)	409	0.35	420	-0.02	0.514	
Business activity likely using electricity (=1)	409	0.23	420	0.01	0.710	

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 0.230. The p-value for the joint F-test for business baseline characteristics is 0.407. 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 B3: Correlations between voltage quality and primary outcomes

	Full N	Mean (SD)	Adjusted average voltage	hours voltage 20% below nominal	Adjusted
Reported hours of bad voltage in past month	3037	23.02 (60.61)	-0.732*** (0.198)	0.161*** (0.052)	
Reported total outage hours in past month	3048	20.50 (34.13)	-0.298*** (0.091)	0.044*** (0.017)	
WTP for perfect reliability and quality (USD)	3057	2.50 (3.46)	-0.019*** (0.005)	0.003*** (0.001)	
WTP for perfect voltage and half outage hours (USD)	3057	1.31 (2.13)	-0.010*** (0.003)	0.002** (0.001)	
WTP for no outages and half bad voltage hours (USD)	825	1.89 (3.11)	-0.005 (0.008)	0.002 (0.002)	
Voltage damage and protection index	3057	-0.02 (0.97)	-0.003* (0.002)	0.001** (0.001)	
Any voltage-related damage, last 12 months (=1)	3057	0.24 (0.42)	-0.002** (0.001)	0.001** (0.000)	
Amt. spent on burnt/broken apps in past year (USD)	2989	6.56 (22.94)	-0.083*** (0.029)	0.017** (0.008)	
Amt. spent on burnt/broken apps (if damage = 1)	692	30.36 (47.69)	-0.089 (0.134)	0.004 (0.024)	
Any reliability protective device owned (=1)	3057	0.25 (0.43)	-0.000 (0.001)	0.000 (0.000)	
Value of protective devices owned (USD)	2587	4.08 (14.51)	-0.035 (0.022)	0.013* (0.007)	
Any alt. energy source used in last month (=1)	3057	0.05 (0.21)	0.000 (0.000)	0.000 (0.000)	
Total no. of appliances owned	3057	8.53 (5.42)	0.003 (0.007)	0.000 (0.002)	
Last month electricity spending (USD)	2959	14.96 (12.87)	0.010 (0.016)	-0.003 (0.003)	
Last month business profit (USD)	1079	88.93 (127.63)	0.058 (0.226)	0.021 (0.045)	
Last month business revenue (USD)	1245	392.85 (574.60)	1.873** (0.901)	-0.355* (0.213)	
Last month business costs (USD)	1179	292.65 (386.76)	1.215* (0.651)	-0.171 (0.146)	
Last month HH income (USD)	1314	301.84 (430.75)	-0.715 (0.748)	0.176 (0.158)	

This table shows a different regression in each cell, with two voltage measurements as the explanatory variables and each row a different outcome variable. Each row represents a different outcome pooling business and household respondents. Profit is measured by directly asking the respondent, rather than by subtracting costs from revenues. Total reported costs are the sum of costs for specific items/activities and are not comprehensive. The columns indicate measures of voltage quality—the independent variables. Voltage is measured by assigning each respondent GridWatch data based on the nearest devices for the year preceding the survey date. Voltage measures are adjusted to account for differences between the distance to the nearest transformer for the respondent and their matched device. Mean voltage in control sites is 219.5V at baseline and 224.6V at endline. 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ Table C10 shows the same using raw matched device data.

Table B4: Testing voltage spillovers in control sites from transformer injection intervention

	Average voltage (1)	Average voltage (2)
Post construction=1	7.37*** (2.00)	6.53* (3.44)
Post construction=1 × Below median distance to nearest injection site=1	-3.79 (2.90)	
Post construction=1 × Distance to nearest injection site (100m)		-0.06 (0.17)
Observations	4936545	4936545
Pre-construction mean, above median distance to injection	220.09	220.09
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. The outcome is average voltage, 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 B5: 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 (1.00)	-0.11** (0.05)	0.09 (0.06)	-0.10* (0.06)
Any voltage-related damage, last 12 months (=1)	3150	0.25 (0.43)	-0.05* (0.03)	0.04 (0.03)	-0.05 (0.04)
Any reliability protective device owned (=1)	3150	0.25 (0.44)	-0.02** (0.01)	0.02 (0.02)	-0.02 (0.01)
Amt. spent on burnt/broken apps in past year (USD)	3080	9.28 (33.80)	-5.77*** (1.37)	0.05 (1.77)	1.23 (1.91)
Value of protective devices owned (USD)	2668	5.49 (23.16)	-2.32** (0.92)	0.36 (1.42)	0.32 (1.63)
Reported hours of bad voltage in past month	3110	43.18 (87.51)	-42.48*** (4.72)	7.60 (7.41)	-9.09 (7.70)
Reported total outage hours in past month	3081	32.15 (31.08)	-29.32*** (2.05)	1.69 (2.60)	-1.18 (2.74)
WTP for perfect reliability and quality (USD)	3150	3.29 (4.41)	-1.41*** (0.21)	-0.34 (0.25)	0.44 (0.28)
WTP for perfect voltage and half outage hours (USD)	3150	1.58 (2.71)	-0.37** (0.16)	-0.17 (0.17)	0.21 (0.21)
WTP for no outages and half bad voltage hours (USD)	850	1.95 (3.34)	-0.07 (0.30)	-0.37 (0.32)	0.99** (0.44)
Total no. of appliances owned	3150	8.59 (5.98)	-0.04 (0.08)	-0.05 (0.35)	0.08 (0.13)
Any alt. energy source used in last month (=1)	3150	0.05 (0.22)	-0.01 (0.01)	0.01 (0.01)	-0.00 (0.01)
Last month electricity spending (USD)	3050	17.72 (16.95)	-3.92*** (0.60)	-1.90* (1.02)	0.53 (0.80)
Last month business profit (USD)	1104	98.60 (143.83)	-6.77 (10.50)	-12.44 (11.53)	3.55 (13.67)
Last month business revenue (USD)	1280	396.21 (625.91)	84.40* (44.75)	-0.80 (51.71)	-92.58 (57.75)
Last month business costs (USD)	1206	276.34 (358.93)	82.04** (36.68)	25.30 (37.84)	-98.48** (49.45)
Last month HH income (USD)	1358	332.33 (473.05)	-34.24 (36.83)	16.93 (41.60)	-75.43 (49.79)

This table shows the difference-in-difference results from the [Equation 2](#) pooling businesses and households. Each row presents results from one regression with a different socio-economic variable as the outcome. All outcomes pre-specified in the pre-analysis plan ([Berkouwer et al., 2019](#)), except for voltage improvements as these were unanticipated.. All variables measuring values are in USD. 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 B6: Impact of transformer injection intervention on main business outcomes

	N	Control Mean (SD)	Post (SE)	Treat (SE)	Post × Treat (SE)
Last month business profit (USD)	1104	98.60 (143.83)	-6.77 (10.50)	-12.44 (11.53)	3.55 (13.67)
Last month business costs (USD)	1206	276.34 (358.93)	82.04** (36.68)	25.30 (37.84)	-98.48** (49.45)
Last month wage and benefits costs (USD)	1330	54.03 (135.87)	14.97* (8.18)	-5.78 (10.38)	-5.75 (11.16)
Last month materials costs (USD)	1266	187.49 (297.45)	72.19** (29.95)	47.78* (27.96)	-93.21** (40.69)
Last month electricity spending (USD)	1594	17.63 (16.99)	-3.92*** (0.73)	-1.74 (1.22)	0.21 (0.96)
Last month spending on alternative fuels (USD)	1658	5.14 (37.42)	-0.95 (1.75)	-1.38 (2.05)	1.17 (1.90)
Last month business revenue (USD)	1280	396.21 (625.91)	84.40* (44.75)	-0.80 (51.71)	-92.58 (57.75)
Estimated increase in revenue w/ perfect electricity (USD)	1044	545.75 (2038.28)	-355.67*** (137.04)	-125.66 (149.10)	30.66 (156.00)
Number of workers	1658	1.99 (1.90)	0.11* (0.06)	-0.06 (0.14)	0.07 (0.09)
Share of men employees	1646	0.31 (0.42)	-0.01 (0.01)	-0.00 (0.01)	-0.00 (0.02)
Share of full-time employees	1628	0.91 (0.21)	-0.05*** (0.02)	0.01 (0.02)	0.00 (0.02)
Business open during any “dark” hours	1658	0.77 (0.42)	-0.08*** (0.03)	-0.01 (0.03)	-0.02 (0.04)
Total hours typically open	1658	12.16 (2.46)	-0.58*** (0.13)	-0.14 (0.19)	-0.16 (0.22)
Applied for loans in past 12 months	1658	0.17 (0.38)	-0.01 (0.03)	0.05 (0.03)	-0.01 (0.04)
Total value of outstanding loans (USD)	1596	350.34 (1174.33)	-11.06 (76.81)	98.83 (90.68)	-183.34* (110.30)

This table shows the difference-in-difference results from the main equation. Each row presents results from one regression with a different socio-economic variable as the outcome. All variables measuring values are in USD. Profit is measured by directly asking the respondent, rather than by subtracting costs from revenues. Total reported costs are the sum of costs for specific items/activities and are not comprehensive. 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. The effects on business costs furthermore do not survive False Discovery Rate (FDR) adjustment for multiple hypothesis testing (Table C8). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B7: Impact of transformer injection on household outcomes

	N	Control Mean (SD)	Post (SE)	Treat (SE)	Post × Treat (SE)
Last month HH income (USD)	1358	332.33 (473.05)	-34.24 (36.83)	16.93 (41.60)	-75.43 (49.79)
Monthly rent (USD)	490	30.78 (25.14)	-3.86*** (1.29)	1.28 (3.46)	-0.52 (1.93)
Share of HH adults (18+) with paid jobs in last 7 days	1484	0.65 (0.36)	-0.02 (0.03)	0.03 (0.03)	-0.04 (0.04)
Household use of dirty cooking fuel (past 3 months)	1492	0.65 (0.48)	0.08*** (0.02)	-0.03 (0.03)	0.04 (0.04)
Last 2 weeks spending on health (USD)	1408	13.22 (34.91)	4.70 (2.88)	-1.37 (2.30)	3.83 (3.91)
Household qualitative assessments index	1492	1.38 (2.26)	-1.38*** (0.16)	0.02 (0.20)	0.03 (0.23)
Perceived safety in area (1-5)	1490	3.51 (0.97)	0.02 (0.07)	-0.17** (0.09)	0.05 (0.12)
Belief that Dumsor is back (1-5)	1486	2.99 (1.27)	1.32*** (0.10)	-0.00 (0.12)	0.07 (0.13)
Expected reliability one year from today (1-3)	1032	2.33 (0.79)	0.32*** (0.07)	0.02 (0.08)	0.02 (0.10)
Loss of perishable food due to reliability (0-2)	1486	0.33 (0.54)	-0.31*** (0.03)	-0.02 (0.05)	0.04 (0.05)
Loss of perishable medicine due to reliability (0-2)	1486	0.04 (0.20)	-0.03*** (0.01)	0.00 (0.02)	-0.00 (0.02)
Household health challenges due to reliability issues	1484	0.00 (1.00)	-0.00 (0.07)	0.07 (0.08)	-0.02 (0.12)
Household study light quality index	1492	0.00 (1.00)	-0.04 (0.06)	-0.06 (0.06)	0.03 (0.07)
Hours per day lightbulbs used for reading or studying	402	0.90 (0.24)	0.08*** (0.03)	-0.00 (0.03)	-0.00 (0.04)
Share of hours per day reading or studying with lightbulbs	1492	0.13 (0.59)	-0.09*** (0.03)	-0.04 (0.04)	0.03 (0.04)

This table shows the difference-in-difference results from the main equation. Each row presents results from one regression with a different socio-economic variable as the 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. 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 B8: Impacts of transformer injection intervention on voltage by baseline voltage quality

	(1)	(2) Below median baseline voltage	(3) Above median baseline voltage	(4) All sites
	All sites			
Post construction	5.94*** (1.74)	10.02*** (2.99)	1.85 (1.32)	1.98 (1.31)
During construction	0.76 (1.09)	2.04 (2.15)	-0.01 (1.07)	0.32 (1.06)
Treat X Post	5.48** (2.48)	8.70** (4.09)	2.20 (2.00)	2.22 (2.00)
Treat X During	2.38 (1.60)	5.65* (2.84)	-0.99 (1.48)	-0.99 (1.47)
Poor baseline quality [PBQ] =1				0.00 (.)
Post construction=1 × PBQ=1				7.92** (3.23)
During construction=1 × PBQ=1				1.44 (2.29)
Treat X Post=1 × PBQ=1				6.46 (4.54)
Treat X During=1 × PBQ=1				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

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. Each column presents results from one regression with voltage as the outcome variable, but for different samples. Subsetting by baseline voltage is done separately for treatment and control sites, so the samples always include an equal number of each. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B9: Heterogeneous impacts of transformer injection intervention on primary outcomes

	(1) Good voltage (device) (below median)	(2) Hours reported bad voltage (above median)	(3) Business importance (high)	(4) WTP for electricity reliability median)	(5) Defensive investments (high)	(6) Appliances owned (above median)	(7) Fridge count (≥ 1)	(8) Worst
Voltage damage and protection index	0.05 (0.12)	-0.03 (0.12)	-0.04 (0.12)	-0.07 (0.10)	-0.05 (0.13)	-0.03 (0.10)	0.07 (0.10)	0.02 (0.15)
Any voltage-related damage, last 12 months (=1)	0.03 (0.07)	-0.02 (0.07)	-0.01 (0.08)	-0.00 (0.06)	-0.02 (0.07)	-0.02 (0.06)	0.02 (0.06)	0.04 (0.09)
Any reliability protective device owned (=1)	-0.00 (0.02)	-0.00 (0.03)	-0.01 (0.04)	-0.05* (0.03)	-0.01 (0.04)	0.00 (0.02)	0.02 (0.02)	-0.02 (0.03)
Amt. spent on burnt/broken apps in past year (USD)	-2.39 (3.70)	2.99 (3.73)	-1.21 (3.73)	-4.10 (3.80)	0.16 (5.00)	-1.49 (3.82)	1.19 (3.51)	0.26 (5.12)
Value of protective devices owned (USD)	-5.20* (3.12)	2.74 (3.86)	0.84 (3.41)	-2.44 (3.43)	4.87 (12.02)	2.75 (3.60)	4.48 (3.04)	-2.03 (2.37)
Reported hours of bad voltage in past month	-14.76 (14.25)	-9.49 (13.23)	-2.16 (13.82)	4.17 (11.25)	-6.62 (12.79)	-12.05 (9.27)	-0.59 (10.15)	-7.26 (16.12)
Reported total outage hours in past month	-0.30 (5.00)	3.02 (3.96)	3.24 (4.83)	-1.71 (3.32)	-5.32 (3.80)	-6.99** (3.38)	-3.15 (3.36)	-1.58 (5.39)
WTP for perfect reliability and quality (USD)	1.11** (0.53)	1.06** (0.52)	0.59 (0.74)	0.83** (0.42)	-0.11 (0.55)	0.66 (0.53)	0.49 (0.41)	2.08*** (0.76)
WTP for perfect voltage and half outage hours (USD)	1.03** (0.41)	0.74** (0.37)	0.13 (0.46)	0.35 (0.33)	-0.14 (0.42)	0.27 (0.35)	0.14 (0.32)	1.25** (0.57)
WTP for no outages and half bad voltage hours (USD)	2.61*** (0.86)	1.68* (0.87)	2.21 (1.46)	0.90 (0.83)	-0.45 (1.18)	0.90 (0.91)	0.12 (0.66)	1.54 (1.33)
Total no. of appliances owned	-0.15 (0.25)	-0.03 (0.27)	-0.14 (0.41)	-0.35 (0.25)	-0.07 (0.33)	0.16 (0.24)	0.05 (0.23)	-0.16 (0.28)
Any alt. energy source used in last month (=1)	-0.01 (0.02)	-0.00 (0.02)	0.06** (0.03)	-0.03 (0.02)	-0.02 (0.02)	-0.00 (0.02)	-0.01 (0.02)	0.02 (0.04)
Last month electricity spending (USD)	-0.58 (1.57)	0.89 (1.31)	-2.22 (1.84)	-0.52 (1.62)	-1.30 (1.87)	-0.69 (1.48)	-1.87 (1.45)	0.64 (2.03)
Last month business profit (USD)	46.86 (29.48)	6.49 (26.10)	24.00 (29.91)	5.95 (28.23)	-22.31 (29.62)	-31.07 (29.50)	14.45 (24.91)	37.57 (53.23)
Last month business revenue (USD)	237.17** (114.63)	40.40 (101.19)	231.01 (156.52)	-38.59 (112.21)	-172.62 (140.55)	-56.45 (105.92)	66.93 (114.66)	64.13 (195.13)
Last month business costs (USD)	66.52 (96.66)	39.74 (82.34)	168.46 (121.84)	-51.50 (94.85)	-109.27 (105.08)	-76.97 (96.53)	-44.15 (91.97)	-92.30 (150.30)
Last month HH income (USD)	42.59 (94.35)	29.57 (87.67)	0.00 (.)	-61.55 (86.75)	14.91 (101.05)	35.72 (80.13)	40.69 (82.82)	150.02 (115.63)

Difference-in-difference estimates of triple interactions with specific baseline customer characteristics. Each cell is one regression. The coefficients correspond to α_1 from the following equation: $Y_{it} = \alpha_0 + \alpha_1 \text{Group} * \text{Treat} * \text{Post}_{it} + \alpha_2 \text{Group} * \text{Treat}_{it} + \alpha_3 \text{Group} * \text{Post}_{it} + \alpha_4 \text{Post} * \text{Treat}_{it} + \alpha_5 \text{Post}_{it} + \alpha_6 \text{Treat}_{it} + \alpha_7 \text{Group}_i + u_{it}$. Good voltage equals 1 for those that are below the median per device measurements. Hours of reported bad voltage equals 1 for those reporting levels of bad voltage above the median at baseline. “High electricity importance =1” if the owner reported that electricity is “very important” or “extremely important”. “High defensive investments” means having at least 1 reliability protective device. Appliances owned equals to 1 if a respondent has more appliances than the median. Fridge count equals 1 if the respondent has at least one fridge at baseline. “Worst” equals 1 if at baseline, the respondent has below median voltage and owns appliances sensitive to voltage but does not own protective devices. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$