Voltage quality and economic activity

Susanna B. Berkouwer Pierre E. Biscaye Maya Mikdash Steven L. Puller
Catherine Wolfram

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Abstract

Voltage quality issues—such as sags, spikes, and fluctuations—are pervasive across many low- and middle income countries, yet their unobservability has hampered large-scale analysis of their economic importance. This paper uses state-of-the-art measurements to shed light on this novel dimension of publicly provided infrastructure, which underpins most modern industrial, commercial, and residential activity. We characterize voltage quality issues experienced by electricity customers in urban Ghana, quantify the associated economic costs, and estimate the causal impact of a modest improvement in voltage quality as a result of quasi-random electricity grid investments. To do so, we combine minute-by-minute customer-level power measurements with detailed panel surveys of more than 1,500 households and small businesses across Accra. The analyses produce three main findings. First, we document widespread voltage problems: approximately 20% of grid electricity is of poor quality (more than 10% below nominal voltage, 230V), including 30% during peak hours. Second, both residential and business customers purchase expensive equipment to protect against voltage problems and are willing to increase monthly electricity spending by 10% for power supply with half of the existing voltage problems. Third, using a differences-in-differences design, we find that a 5V increase in average voltage—resulting from the construction of additional transformers at selected sites—reduces the frequency of appliance damages at treatment sites relative to control sites, but generates no other economic impacts after 1 year. Longer-term and systemic improvements in electricity usage may require more significant voltage quality improvements through additional infrastructure investments.

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Berkouwer: The Wharton School, University of Pennsylvania and NBER, sberkou@wharton.upenn.edu. Biscaye: Department of Agricultural and Resource Economics, University of California, Berkeley, pbiscaye@berkeley.edu. Mikdash: Department of Economics, Texas A&M University, mmikdash@tamu.edu. Puller: Department of Economics, Texas A&M University and NBER, spuller@tamu.edu. Wolfram: The Sloan School of Management, Massachusetts Institute of Technology and NBER, cwolfram@mit.edu. We thank participants at the UC Berkeley Energy Camp for helpful comments. We thank the Millennium Challenge Corporation (MCC), the Foreign, Commonwealth and Development Office (FCDO), the Kleinman Center for Energy Policy, and Analytics at Wharton for generous financial support. This study has Institutional Review Board approval from the University of California at Berkeley (ID 2017-12-10599) and the University of Ghana Institute of Statistical, Social and Economic Research (ISSER) Ethics Committee (ECH 153/18-19). We thank Ivan Bobashev, Keanan Gleason, Miranda Lambert, Paula Meloni, Prema Sai Narasimhan, Geetika Pandya, Adam Streff, Derek Wolfson, and Paula Zamora Riano for excellent research assistance and Karen Notsund, Noah Klugman, Joshua Adkins, and the entire team at nLine for their support. We thank the University of Ghana ISSER, in particular Dr. Simon Bawakyillenuo and Dr. Ralph Amah, for superbly implementing field activities, as well as Kwame Abrokwah, Kelvin Dogbe, Agnes Okyne, and Daniel Agyei, for superbly implementing the GridWatch deployment.

1 Introduction

Recent improvements in data science—such as satellite imagery, internet-of-things, and machine learning—have massively expanded the scope and precision of economic variables that can be measured. Improved data collection can drive improved economic performance: recent examples include contract monitoring, environmental regulatory enforcement, or parametric insurance. It also enhances researchers' abilities to assess the technological determinants of economic performance. Within the electricity sector, 'big data' has enabled research on affordability, pricing, and formality, for example, but has yet to be widely apply to other issues including capacity, availability, and reliability that are particularly important in developing country contexts.[1] In this paper, we leverage the large-scale collection of spatially and temporally high-frequency power quality measurements to provide unparalleled insight into a little-understood yet core underpinning of modern energy access: voltage quality.

In most countries, electric utilities are charged with maintaining grid-level voltage within ±5% of targeted voltage.[2] Utilities in low-resource contexts often fail to meet that goal (see for example Blimpo and Cosgrove-Davies, 2019; Jacome et al., 2019; Meeks et al., 2023; and WB, 2020). However, the United Nations (UN) Sustainable Development Goal 7—*"affordable, reliable, sustainable and modern energy for all"*—does not even mention voltage (UN, 2022). World Bank reports on energy often either do not discuss voltage or depend on self-reported data collected in households surveys, which—as we will discuss in this paper—can be very noisy (WB, 2020; WB, 2021). While the World Bank's Energy Sector Management Assistance Program (ESMAP) Multi-Tier Framework (MTF) quantifies electricity access and reliability in detail (ESMAP, 2015),[3] it only defines two tiers of voltage quality: whether or not voltage problems affect appliance use. Yet even this relatively narrow definition of voltage quality is difficult to measure. Understanding the costs of poor voltage quality and the economic payoffs from voltage improvements—in particular relative to improvements in access, reliability, or affordability—is crucial in enabling resource-constrained utilities to optimally target grid investments.

This paper documents and studies the economic implications of pervasive voltage quality problems using evidence from Accra, Ghana. A key contribution of this paper is the collection of 337 million customer-level reliability and voltage quality measurements over 6 years. In addition, we collect panel socioeconomic survey data from over 1500 households and firms across Accra. We conduct detailed descriptive data analyses characterizing the relationship between voltage quality and economic activity. We then estimate the causal impact of a $14 million quasi-randomly placed grid investment—part of the Millennium Challenge Corporation (MCC) Ghana Power Compact—on a

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

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

[3] For example, under 'availability' it has five tiers for daily availability and five tiers for evening availability.

wide range of socioeconomic outcomes.

The analyses generate three key findings. First, we document significant voltage problems. Average voltage at baseline is 219 volts (V), which is 11V (5%) lower than the targeted nominal level of 230V. Voltage is more than 10% (20%) below the nominal level 5.3 (1.2) hours per day, or 17% (5%) of each hour on average. Customers experience an average of 250 'spells' each month when voltage drops at least 10% below nominal for at least two minutes, lasting a total of 131 hours and including an average of 11 spells lasting 84 hours where voltage drops more than 20% below nominal. Such fluctuations are likely highly damaging for commercial and residential appliances: machinery cannot operate at full capacity, and protective components malfunction causing appliances to burn.[4]

Second, these voltage issues, as well as their economic costs, are salient to respondents. Thirty-one percent of businesses report voltage to be an important obstacle to operations, and 25% of respondents reported owning voltage protective devices to try to protect appliances against bad voltage, valued at $51 on average (for scale, this represents approximately 1% of both annual household income and annual business revenues in the sample).

In a context such as this, with widespread persistence of voltage quality problems, can distribution grid investments meaningfully improve economic outcomes? Using a difference-in-differences approach, we show that grid investments at 76 sites where a new transformer was constructed increase average voltage by almost 5V relative to 75 comparable sites that did not receive such an investment, and reduce by 37 hours the time spent with low quality voltage in a given month. This causes a marginally significant reduction in the ownership of protective devices and subsequent voltage-related damages. However, it has no significant impact on major household and firm socioeconomic outcomes including electricity spending, appliance ownership, business profits, and household income. This is true across respondents with different baseline levels of voltage quality and of electricity reliance.

These null effects could be because the improvements in voltage quality were not big enough to trigger significant changes in investment decisions and electricity use. Relatedly, control sites experienced significant improvements in power quality over the study period, which might have made the additional improvements in treatment sites less impactful. Finally, investment in new appliances could have been hindered due to the COVID-19 pandemic, potentially also contributing to the null effects that we observe. Because of the lack of impact of transformer construction beyond immediate voltage-related outcomes, calculations of the benefit-cost ratio under different assumptions suggest it is unlikely to exceed one.

This paper contributes to a small set of research papers on voltage quality issues in low- and middle-income countries. Jacome et al. (2019) measure power quality among 25 households in rural Tanzania, finding that this is often more than 10% below nominal voltage. Meeks et al. (2023) use voltage indicators at the transformer level to study how the roll-out of smart meters affects voltage fluctuations and electricity consumption. Voltage fluctuations, voltage sags (where

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

voltage is more than 10% below nominal), and other indicators of poor voltage quality can all have important economic impacts by affecting the productivity of appliances and machinery. 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). The results contribute to broader literatures on the impacts of poor grid electricity service in developing countries and on the constraints and challenges for business productivity and growth (Aterido et al., 2011). Our paper also relates to studies that uses rich new sources of data to answer economic questions, such as the use of satellite imagery for understanding the economic impacts of climate change (see for example Carleton et al., 2022), machine learning techniques to identify causal treatment effects (see for example Athey and Imbens, 2019), and the use of mobility and location data to advance quantitative spatial economics (Redding and Rossi-Hansberg, 2017).

This paper provides a framework to measure the severity of voltage quality and to evaluate the impact of power distribution network improvements in low-resource contexts. Utilities that face challenges in creating a modern power system must make strategic decisions on how to allocate scarce resources within the electricity sector. These choices involve choosing between expanding access to communities without grid connections, improving generation capacity to support the continuous operation of high utilization equipment, or improving the distribution network to enhance voltage quality. *Are investments in improving voltage high return?* Our project cannot provide a universal answer because power networks vary substantially in voltage quality. However, we use our framework to address the question for a given power grid in a large city in Sub-Saharan Africa where power reliability problems are ubiquitous. The power monitoring infrastructure that we put in place forms a foundation to address this question. Our application, using a difference-in-differences approach in Accra, provides an important first data point by analyzing the impact of a grid investment on voltage and subsequent effects on economic outcomes.

2 Voltage quality: importance and measurement challenges

The goals of global energy policy focus primarily on two dimensions of electricity – access and reliability. The World Bank quantifies these dimensions in nuanced detail, delineating 12 distinct categories of "capacity" and 10 of "availability" and detailed metrics of each category.[5] However, voltage is only viewed in the World Bank framework with two categories: "household experiences voltage problems that damage appliances" or "voltage problems do not affect the use of desired appliances" (WB, 2015). This very coarse categorization of what is clearly a complicated and nuanced phenomenon is likely driven by limited data availability on voltage. The lack of granular data has prevented voltage quality from being adequately factored into grid planning and key economic indicators.

[5] These categories are described in World Bank's Energy Sector Management Assistance Program (ESMAP) Multi-Tier Framework (MTF) (ESMAP, 2015).

Most of the world's population—including Ghana—has a nominal voltage of 230 volts (V) (International Electrotechnical Commission, 2023). The U.S. uses a nominal voltage of 120V (with a split-phase system that can also supply 240V), and other countries use other voltage levels largely chosen for historical reasons. Utility regulators normally set the target voltage mean and range for electricity distribution, and appliances are designed to use voltage within this range. Meeting defined voltage and frequency requirements is critical to ensuring reliable electricity supply, which is in turn fundamental to maintaining secure and stable power systems (IEA, 2022).

2.1 Types of voltage quality issues

Most regulators limit the amount of time voltage, as experienced by customers, can deviate from nominal voltage by more than ±5% or ±10%. In practice, defining 'bad' voltage is complicated. During voltage sags—when voltage falls below the nominal range—appliances often cannot function properly. Lightbulbs will dim or flicker. Some appliances cannot be turned on, particularly if the voltage falls to more than 20% below nominal. Others will experience failure of protective components, while other components continue to function, such that long-duration sags can damage appliance non-linearly. Voltage spikes—extreme increases often lasting only microseconds—can cause significant damages to plugged-in appliances. These are rare but sometimes occur as power returns after an outage. Voltage surges—modest, but longer duration, increases above the nominal voltage range—are less damaging than voltage sags as well as less common (we present data on this from Ghana in Section 3).

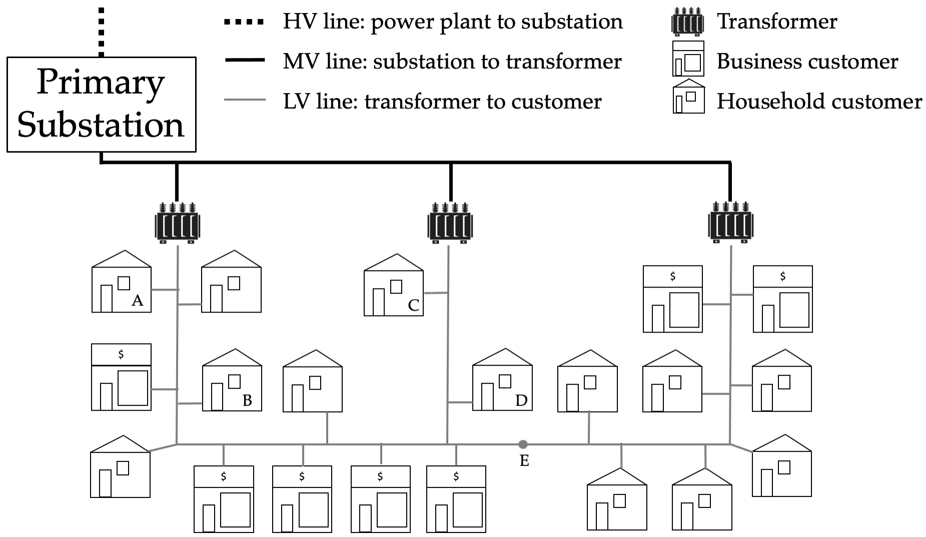
How voltage fluctuations affect appliances is complex, non-linear, and not well understood. A single short but large voltage spike or drop can cause more damage than a more moderate but lengthier voltage surge or sag. Fluctuations may also affect appliances differently than a lengthy period of low voltage.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

2.2 Causes of poor voltage quality

In most countries, electricity is transmitted from power stations to primary substations via high voltage (HV) cables, and then via medium voltage (MV) cables on to transformers, and finally via low voltage (LV) distribution lines to customers at levels that are safe for electric appliances used by customers. Figure 1 presents a schematic.

Transformer load and distance to transformer are key drivers of poor voltage quality. Transformer load is the aggregate electricity demanded by all customers connected to a transformer. When load exceeds the transformer's capacity, the transformer transmits insufficient power to meet demand, causing voltage sags. Voltage is often lower in the evening when electricity demand is

Figure 1: Schematic of local electricity distribution network



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

greatest. Similarly, variation in load increases the variability of customer voltage. Excessive distance to the nearest transformer worsens voltage due to impedance in LV lines and due to the increased load between the transformer and the customer (Jacome et al., 2019). The electricity grid intervention that we study (which we discuss in detail in Section 5) adds new transformers to the grid, reducing the load for individual transformers and also reducing the distance between customers and their nearest transformer.

Figure 1 visualizes these dynamics in an example grid. Households A and C should on average experience similar voltage because both are very close to the transformer and there is no other customer drawing load between them and the transformer. Household D will have worse voltage than household C because of the increased distance to the transformer, but better voltage than B because there are fewer customers between household D and the transformer than between household B and the transformer. Adding a new transformer at location E should improve electricity quality for household D as the distance to their nearest transformer is significantly reduced. It may also improve power for customer C, as the load on their nearest transformer is significantly reduced.

Another factor that can affect voltage quality are power outage events. In the short run, the inrush of electricity current after an outage can sometimes cause voltage spikes. In the long run, outages can degrade LV lines and increase impedance along LV distribution lines.

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

Recent research has documented that voltage in low- and middle-income country contexts often falls outside the nominal range (see Jacome et al. (2019) and Meeks et al. (2023) for examples from

Zanzibar and Kyrgyzstan).[6] However, a lack of large-scale data has limited large-scale research on the economic impacts of poor voltage quality. Most utilities and regulators have no way of measuring voltage as experienced by customers.[7] This problem is exacerbated in LMICs, where resource constraints prevent them from investing in improved technologies: the widespread deployment of smart meters, for example, can be prohibitively expensive (Dutta and Klugman, 2021).

Existing research therefore often turns to self-reported data, but this can be coarse. Twenty percent of enterprises in Kenya, 39% in Nepal, and 56% in São Tomé and Príncipe surveyed in the WB Enterprise Surveys report 'low or fluctuating voltage' as a constraint to operations (WB, 2020). In Jacome et al. (2019), two-thirds of the 151 surveyed households report 'voltage fluctuations in the past month', and in Meeks et al. (2023), more than 70% of the 880 surveyed households report 'at least one voltage fluctuation per week.' Self-reports may also be unreliable as voltage fluctuations can be difficult for customers to observe.

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

3 Measuring voltage quality in Ghana

Ghana achieved high levels of electricity access earlier than most sub-Saharan African countries, with 64% of households connected in 2010 compared to the regional average of 33% (World Bank, 2010). From 2012-2016, Ghana experienced a severe power crisis during which the electric utility was required to resort to long periods of rolling blackouts to address power shortages. This crisis has been covered in the media (The Guardian, 2015; Al Jazeera, 2016; New York Times, 2016; BBC, 2016) and in academic research (Abeberese et al., 2019; Aidoo and Briggs, 2019; Briggs, 2021; Hardy and McCasland, 2019).[8]

Access and reliability have improved significantly in Ghana in recent years, with household electricity access now 86% and outage duration down 56% (SE4All, 2022; Kumi, 2020). Less attention has been given to voltage quality, even though Google trends for searches of terms related to voltage

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

[7] Many utilities have substation-level monitoring systems, but these only detect HV and MV outages (our data from the GridWatch system described below show that LV outages can in some settings comprise a majority of power outages), and does not measure customer-level voltage.

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

quality and to outages in Ghana over the last 5 years suggest they are of similar importance to customers (Figure A1).

We collaborated with engineers to deploy 1,124 GridWatch devices collecting minute-by-minute power quality data across much of the Accra metropolitan region for more than five years (Figure A2 shows a picture of the device). Each device is plugged in with either a household or business, and the participant receives financial compensation for each month they keep the device plugged in.[9] This generates spatially and temporally high-frequency data on voltage and outages as experienced by households and firms, resulting in over 337 million observations which we aggregate to the hour level for analysis. To the best of our knowledge, this is the first large-scale collection of customer-level outage and voltage data in any low- or middle-income country.

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

We find that actual voltage deviates substantially from the target of 230V. In Figure 2, we use data collected between June 2018 and April 2023 to illustrate systematic patterns in Ghana and compare the experience in Ghana to other locations. Panel A of Figure 2 displays data for 20 randomly selected devices during an arbitrarily chosen week (January 2020). Several patterns are worth highlighting. First, there is significant heterogeneity in average voltage across customers. Second, customers often experiences fluctuations outside the recommended range. Third, voltage is consistently worst between 7–10pm, when load is highest. Fourth, nearly all deviations outside the nominal range are the result of voltage sags.

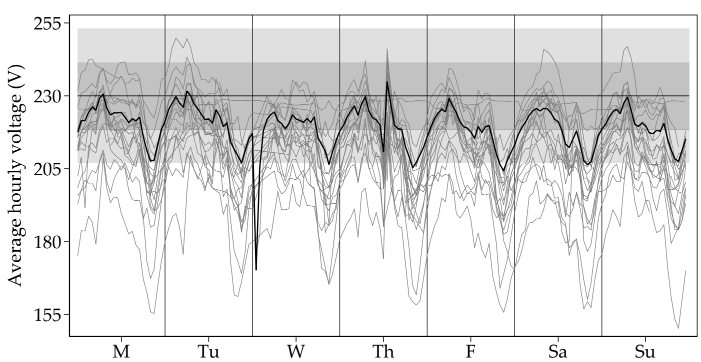
Panel B of Figure 2 compares Ghana's average absolute deviation from nominal voltage with data from Kenya (Wolfram et al., 2023) and the United States (Pecan Street, 2018). Voltage in the U.S. is within 3% of nominal voltage 95% of the time. However, median voltage deviates 10V from nominal in both Kenya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

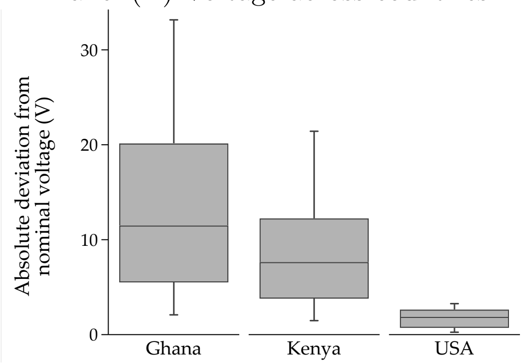
Table 1 presents several voltage quality indicators designed to give a comprehensive picture of customer-level voltage quality. Panel A shows that average voltage over the period from March 2019-November 2020 was 219V, outside the voltage rating range for most appliances in Ghana (220–240V). In a given hour, voltage was 10-20% below nominal 17% of the time and more than 20% below nominal 5% of the time on average. The average share of hours more than 10% below nominal rises to over 30% during peak load hours in the evenings. Voltage sags are significantly more common than power outages, which are experienced on average 2.5% of the time.

[9] Section 5 presents more information on site and respondent selection. Klugman et al. (2019) and Klugman et al. (2021) provide more information on the technology and the deployment.

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

Figure 2: Customer-level voltage quality





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

Table 1: Baseline measures of power quality

Panel A: Hourly data

	Mean	SD	Min	50^{th}	90^{th}	Max
Mean voltage during hour	218.92	21.51	23	222	241	418
Share of hour voltage >20% above nominal	0.00	0.01	0	0	0	1
Share of hour voltage 10-20% above nominal	0.02	0.11	0	0	0	1
Share of hour voltage 10-20% below nominal	0.17	0.33	0	0	1	1
Share of hour voltage >20% below nominal	0.05	0.21	0	0	0	1
Share of hour with no power (outage)	0.03	0.15	0	0	0	1
Any voltage >20% below nominal	0.09	0.28	0	0	0	1

Panel B: Monthly data

	Mean	SD	Min	50^{th}	90^{th}	Max
Hours with no power (outages)	14.24	14.86	0	10	33	146
Number of spells with min voltage >200	206.96	243.81	0	109	572	922
Number of spells with min voltage btwn 184-200	31.74	48.30	0	10	93	224
Number of spells with min voltage <184	10.77	16.81	0	2	34	97
Total hours in spells with min voltage >200	15.43	17.89	0	8	42	70
Total hours in spells with min voltage btwn 184-200	31.10	42.76	0	8	94	181
Total hours in spells with min voltage <184	84.15	160.12	0	0	347	641

Summary statistics for different measures of power quality from March 2019-November 2020 before transformer injection activities were completed, using data from 441 GridWatch devices in 138 sites. Outages are measured at the site level using data from all devices in a site. Panel A includes 2,872,508 device-hour observations, computed from thirty 2-minute observations in each hour. Panel B includes 6,871 device-month observations, taking the sum of hourly values by device within each month for the first four rows, and taking sums across individual low-voltage spells recorded by device within each month for the remaining rows. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

In Panel B, we aggregate hourly Gridwatch device data to the monthly level to provide a description of the frequency and duration of periods with low voltage. Consider low voltage events in which the minimum voltage fell within 184-200 V, which is a range outside appliance ratings. On average, a device experiences 32 such spells per month, lasting an total of 31 hours each spell. For more severe spells where the minimum voltage was less than 184V, devices averaged 11 such spells per month with each spell averaging 84 minutes. A comparison of median and means suggests that more extreme voltage sags are concentrated among certain devices. Our detailed measurements of the voltage experienced by customers provide crucial new evidence on power quality in this low-income country. It reveals that voltage frequently deviates from the range for which appliances are rated, and these instances of voltage sags can be of considerable duration.

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 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. These three mechanisms may furthermore lower long-term investment by lowering the expected value of appliances.

To study these channels, we survey 1,575 electricity grid customers—746 households and 829 businesses—across 151 distinct study sites in Accra where GridWatch devices were deployed.[11] The descriptive analyses use baseline surveys, conducted in March-April 2021.

Characteristics of household respondents are fairly similar to those of other households in the Accra Metropolitan Area (Table A1). Businesses in the survey sample are primarily micro-enterprises with 1 or 2 employees including the owner or manager, and consequently mean employees, revenues, and profits are much smaller than the median for businesses in Accra from the 2013 census of Ghanaian businesses (Table A1). The most common business activities are small retail operations (44%), personal care services such as hair and nail care (16%), manufacture and repair of clothing (15%), and food and beverage services (5%).

4.1 Correlates of customer-level power quality and reliability

Voltage problems and power outages are widely prevalent and do not appear to be concentrated based on income or other demographic factors. Table 2 documents correlations between electricity quality and reliability and socioeconomic and geographic characteristics.

Monthly hours with low voltage are not statistically different for wealthier respondents or for higher-income households or higher-revenue businesses. The only characteristic correlated with voltage quality is distance between the household or business and the nearest transformer: being 100 meters farther away is associated with an additional 33 hours of low voltage per month, a 19%

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

increase. This aligns with the causes of poor voltage quality discussed in Subsection 2.2 (Figure A3 shows this relationship graphically).

Table 2: Baseline correlates of power quality and reliability

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

Notes: This table shows the results from separate regressions estimating the correlations between measures of power quality and reliability—from GridWatch devices deployed in the same site where respondents are sampled—and survey respondent characteristics. All regressions control for respondent sex and age, whether the survey location is the site of both a household and a business, and whether the location is owned by the household/business. The wealth index includes whether the respondent is located in a structure with a high-quality roof material, the same for a high-quality wall material, the count of appliance types owned by the respondent, and whether the respondent has completed secondary education. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

In the case of outages, wealth is correlated with electricity quality. A one standard deviation increase in the wealth index—consisting of dwelling or business structure quality, appliance ownership, and education—is associated with a 0.6 hour (4%) reduction in outages per month. Respondents that share their electricity meter—likely to be less wealthy—experience 1.4 (10%) more outage hours per month. This could reflect a causal relationship, customer sorting on attributes, or utility investment in higher-revenue areas.

These correlations suggest some relationship between outages and wealth. However, for the measure of electricity service that is the focus of this paper—voltage quality—the prevalence of poor quality voltage cuts across wealth and income. Customers may be less able to identify areas with better voltage quality, or utilities may not be precisely targeting voltage improvements.

4.2 Customer self-reports of power quality and reliability issues

The voltage sags and outages that we measure with the GridWatch devices affect customers and we can observe this in the survey data. Table 3 reports summary statistics for households' and businesses' experiences with electricity issues.

In March-April 2021, respondents reported 39 hours of power outages and 47 hours with bad voltage over the past month on average. Self-reported outages correlate strongly with GridWatch-measured outages (see Figure A4), but respondents under-report actual outages by more than half. There is a much weaker correlation for voltage, with customers under-estimating the frequency of low quality voltage by an order of magnitude. Individuals may only be able to detect low-quality voltage well below the threshold of 10% below nominal voltage we use to define low voltage with the GridWatch data, and may not observe voltage issues during periods they are not actively using appliances.[12]

Table 3: Baseline household and business electricity quality issues

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

Values are in USD. Value of voltage protective devices are among those with any such devices. Spending on burnt appliances is among those reporting any voltage-related damage. Voltage protective devices include general purpose voltage stabilizers and more specialized devices such as fridge guards and TV guards. Alternative energy sources include generators, solar panels, and wet cell batteries. Only a subset of respondents in the baseline survey were asked their WTP for reduced voltage fluctuations. In both WTP scenarios with partially improved aspects of electricity service, the hypothetical connection is otherwise perfect (i.e., some outages but no voltage fluctuations or some voltage fluctuations but no outages).

One direct measure of the cost of poor power quality is damages to appliances due to voltage issues: 27% of respondents report at least one such instance in the past year. These respondents spent $39 on repairs or replacements (around 10% of monthly household income and business revenue). A direct implication is that customers purchase equipment that protects appliances from bad voltage, and that equipment is costly. 26% of respondents have at least one voltage protective device, with an average estimated value of $51 (equivalent to around 3 months of average electricity spending).[13]

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

[13]These include general purpose voltage stabilizers (15% of customers) as well as more specialized devices such as fridge guards (11%) and TV guards (4%), all of which protect against voltage fluctuations which can damage

Electricity issues may also disrupt business operations. Outages impose clear costs by preventing activities that require electric appliances, and 92% of businesses report that outages are an obstacle to business operations. Effects of voltage fluctuations are less clear, but 31% of businesses report them as an obstacle to operations.

One issue is that access to alternative energy sources (generators, solar panels, wet cell batteries) is limited. Just 5% of respondents have any such energy source meaning nearly all customers have no alternative to power their electric appliances if grid electricity service is poor.

4.3 Relative value of reliability and voltage quality improvements

A resource-constrained electric utility may need to choose between reliability improvements and voltage improvements. Which of these would customers prefer? We find through a series of stated preference exercises that customers place significant value on reducing voltage problems, on par with the value they place on avoiding outages.

First, we use a standard set of stated preference questions to measure willingness to pay (WTP) for six 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, first asking about a randomly chosen price (USD 1.68, USD 3.35, USD 5, or USD 6.70) and then iteratively asking about either higher or lower prices based on the prior response.[14] Table 3 shows that respondents are WTP on average an additional USD 3.4 per month (an 18% increase in electricity spending) for access to an electricity connection with no voltage fluctuations or outages (this includes around 50% of respondents who had a WTP of USD 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 (USD 1.6 and USD 1.9 per month, respectively; Figure A5 presents the full distributions), representing around 10% of monthly electricity spending.

We also ask respondents how they would prioritize the allocation of hypothetical government funds across five different potential investment areas: reduced power outages, improved voltage quality, improved schools, reduced traffic congestion, and improved access to piped water. Around one-third of respondents report that they would evenly split the allocation across the five areas. Excluding these, respondents would on average allocate 15% of the funds to improving voltage quality, which is again similar to the mean amount allocated to reducing outages (17%). Improving schools (29% of the funds) and access to piped water (26%) are the relative priorities.

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

appliances.

[14] This follows other papers eliciting WTP related to electricity 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).

in reliability indicate that poor voltage quality may impose costs of a similar magnitude.

5 Identifying the causal impact of grid voltage investments

In 2014, the Millennium Challenge Corporation (MCC) signed the Ghana Power Compact to disburse $316 million in funding towards electricity network improvements in Ghana (MCC, 2014), of which $14 million was spent on low-voltage (LV) line bifurcation in the Achimota, Dansoman, and Kaneshie districts of Accra, Ghana,[15] which corresponds to expenditures of around USD 286 per household. What was the impact of this investment? Employing a difference-in-differences empirical strategy, we use pre- and post-investment data to estimate effects on power quality and economic outcomes.

5.1 Low-voltage line bifurcation

Line bifurcation involves adding a new transformer to the LV network with the goal of reducing the distance between customers and their nearest transformer. MCC's line bifurcation investments aimed "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). Figure 3 Panel A provides an illustration. As discussed in Subsection 2.2, the reduction in distance and in transformer load should increase average voltage and reduce voltage variance, in particular for customers whose distance to a transformer decreases the most.[16]

MCC contracted out the selection of transformer injection locations within each district, as well as the process of transformer construction, to a private sector contractor. The contractor targeted grid segments approximately 200 to 300 meters from the nearest transformer, but other than this had very limited local data with which to select sites where new transformers were to be injected. They did not have access to any type of socioeconomic or demographic characteristics or data on metered connections, bill payment rates, or electricity demand (sub-district electricity data in general is largely unavailable as the utility only prepares district- and city-wide data). The one exception to this is that the contractor obtained analog readings of transformer-level load measuring the highest instantaneous load experienced at a transformer since the last reading. However, these must be reset manually and are not reset at a fixed schedule, and are therefore a crude and noisy measure of load. We therefore argue that, conditional on distance to the nearest transformer, line bifurcation treatment sites were selected without obvious regard for the outcomes we study.

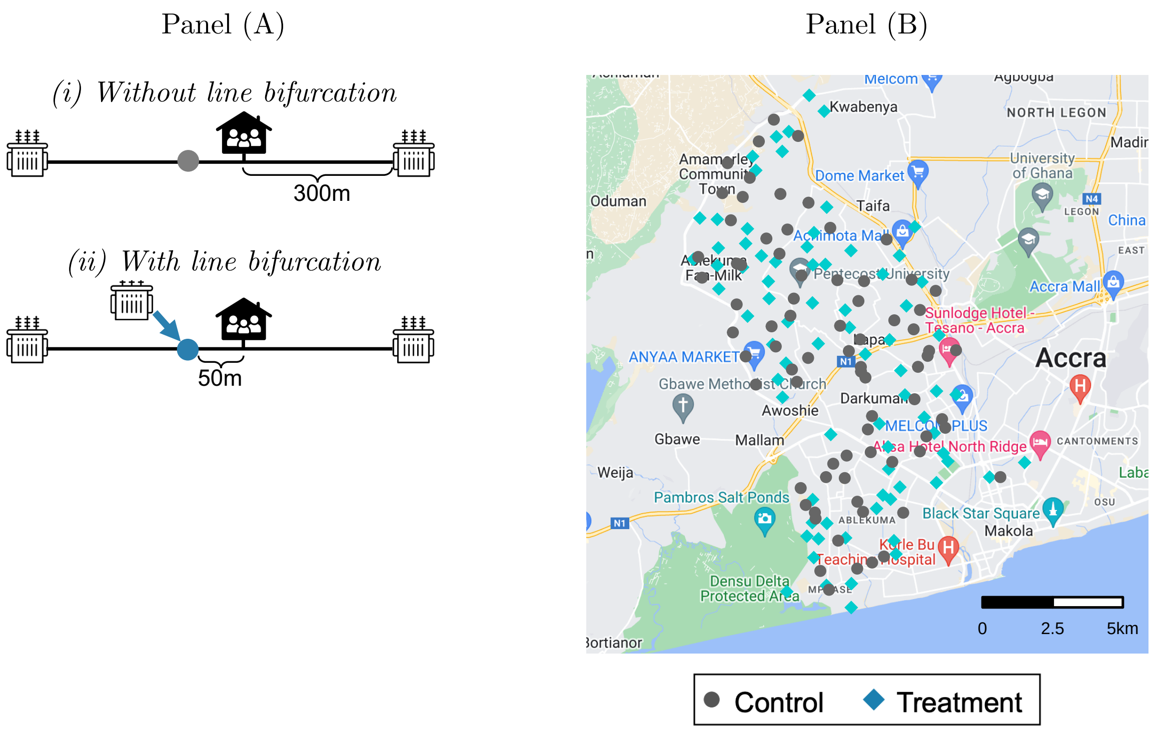
The contractor selected 76 locations for transformer injection ('treatment sites') in the three

[15] The original amount was $498 million but this was reduced to $316 million in 2019 (2022, June 6). Of this, $220 million funded the Electricity Company of Ghana (ECG) Financial and Operational Turnaround Project (EFOT) with the aim of improving the technical and operational quality of the utility, which included a $63 million 'technical loss reduction' component that included the line bifurcation activity.

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

study districts Achimota, Dansoman, and Kaneshie.[17] Using spatial data covering the entire electricity network in Accra, we then identified all locations on the grid that were between 200 and 300 meters from both the nearest transformers and the planned new transformers, and then randomly selected 75 locations from this set ('control sites') matching the main criterion for transformer injection selection. The 76 treatment sites and 75 control sites, shown in the map in Figure 3 Panel B, comprise the 151 sites of our study sample.

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.

5.2 Data

For each transformer or placebo injection location, we use maps of the distribution network to define boundaries of treatment and control sites (Figure A6 presents an example). We first identify segments of LV lines that are at most 200 meters from the potential injection location along the LV network and at least 300 meters from an existing transformer, and then identify the area within 25 meters of these LV segments. Customers within these boundaries are those whose electricity service would be most affected by a transformer injection.

[17] The total number of injections was 88; we exclude a small number of sites that are located very close to each other to avoid spillovers.

GridWatch devices were deployed within site boundaries starting in June 2018 and began collecting voltage quality and reliability data. Deployment to all 151 treatment and control sites was completed by March 2019. New transformers were constructed between October 2020 and March 2021. We focus on GridWatch data collected between March 2019 and April 2023. Figure A7 presents a timeline.

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

Baseline surveys with 6-7 businesses and households in each site were conducted in March–April 2021 and endline surveys in July–September 2022.[18] The surveys consisted of questions related to household and business socioeconomic characteristics, appliance ownership, use of electricity and alternative energy sources, and experiences with electricity quality. Each respondent is assigned the voltage data from the GridWatch device nearest to their location and the outage data for the site they are located at (as outages are detected at the site level).

Of 2,001 respondents surveyed at baseline, 1,575 were surveyed at endline (25% of households and 17% of businesses attrited). Attrited respondents differ along a small number of variables commonly associated with attrition such as age, household size, and rental status (Table C1), but are similar along most other socioeconomic characteristics and across treatment status (Table C2). The final analysis sample includes 363 households and 409 businesses at the 75 control sites and 383 households and 420 businesses at the 76 treatment sites.[19] As discussed in Section 4, sample households are similar to other households in Accra while sample businesses are primarily microenterprises (Table A1).

While our empirical strategy is a difference-in-differences approach and identification therefore does not require baseline balance, we conduct a battery of tests examining baseline balance between control and treatment sites. Levels and trends in mean electricity reliability and voltage by site treatment status are statistically indistinguishable before the line bifurcation intervention (Figure A8). Characteristics of survey respondents at baseline are balanced across treatment and control sites in terms of demographics, self-reported electricity reliability, appliance ownership, electricity and energy use, household characteristics, and business characteristics (Table A1).[20] The distributions of distance between each survey respondent and the nearest existing transformer prior to line bifurcation are statistically indistinguishable (p-val $= 0.14$) across control and treat-

[18] Due to COVID-19 related delays, baseline surveys were conducted while line bifurcation construction activities were being completed. However, voltage quality did not improve until April 2021 (Figure A8), and this window is likely to have been too short for households or businesses to notice any sustained improvement, let alone act on this improvement and have it reflected in socioeconomic outcomes. In support of this, we find no baseline differences in outcomes by treatment status (Table A3).

[19] Due to a lack of evidence on impacts of changes in voltage quality, power calculations to determine sample size were based on assumptions about the likely impacts on outages.

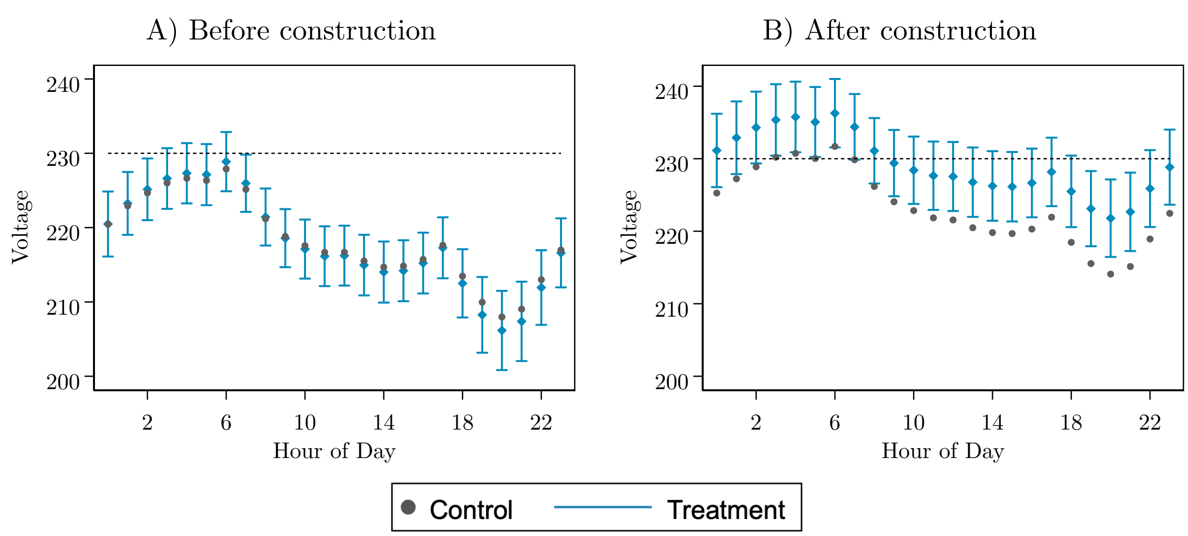
[20] We fail to reject that the difference in means is 0 by site treatment status for nearly all characteristics. The p-value for a joint F-test for household characteristics is 0.185, while that for business characteristics is 0.442.

ment sites (Panel A of Figure A9).[21,22] Nighttime radiance data from VIIRS are also balanced prior to the intervention (Figure A10). This evidence of baseline balance and parallel pre-trends, in conjunction with the institutional design of the grid investments, support the logic that a difference-in-differences design will identify causal impacts of electricity grid improvements.

5.3 Results: Impact of construction on power quality

We first analyze impacts of line bifurcation on outages and voltage using the high-frequency GridWatch device data. Figure 4 plots average voltage by hour of day and treatment status before and after construction of new transformers.

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. SE clustered by site. Figure C1 shows impacts on outage duration.

Panel A shows that daily patterns in average voltage were identical in treatment and control sites pre-construction. 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, such that average voltage in treatment sites is within ±5% of nominal voltage across all hours of the day. An event study version of this estimation shows that voltage gains in treatment sites were stable for a year after construction completion, but decreased slightly and were no longer significantly different from

[21] Respondents already close to an existing transformer at baseline are those near the boundaries drawn around actual or placebo transformer injection locations.

[22] Prior to construction, respondents at control (treatment) sites are on average 233 (253) meters from the nearest transformer (Panel A). This remains unchanged for control respondents but decreases by 163 meters for the median treatment respondent (Panel B). Panel C of Figure A9 shows the distribution of change in distance to the nearest meter from baseline to endline for treatment and control sites. Small changes in distances for control respondents reflect GPS measurement accuracy; larger changes may indicate a new transformer in a treatment site becoming their new closest transformer.

0 starting in August 2022 (Panel C of Figure A8). It is worth noting that control sites also experienced an increase in average voltage of 5V relative to the pre-construction period, such that average voltage at control sites post-construction is within ±5% of nominal voltage at all hours except during peak load hours (6–9pm).

Pooling these data, our main estimation uses the following panel fixed effects difference-in-differences regression:

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

Y_{it} is an electricity outcome experienced by device i at time t. $\boldsymbol{\Gamma_s}$ are site fixed effects, which subsume the 'Treat' dummy. $\boldsymbol{\Gamma_t}$ are time fixed effects that vary across regressions. β_1 and β_2 capture changes in voltage levels after and during construction relative to the pre-construction period. β_3 captures the treatment effect of interest, while β_4 captures any effects during construction.[23] Standard errors are clustered by site in all regressions. Table 4 presents the results.

Table 4: Impact of transformer injection intervention on outages and voltage

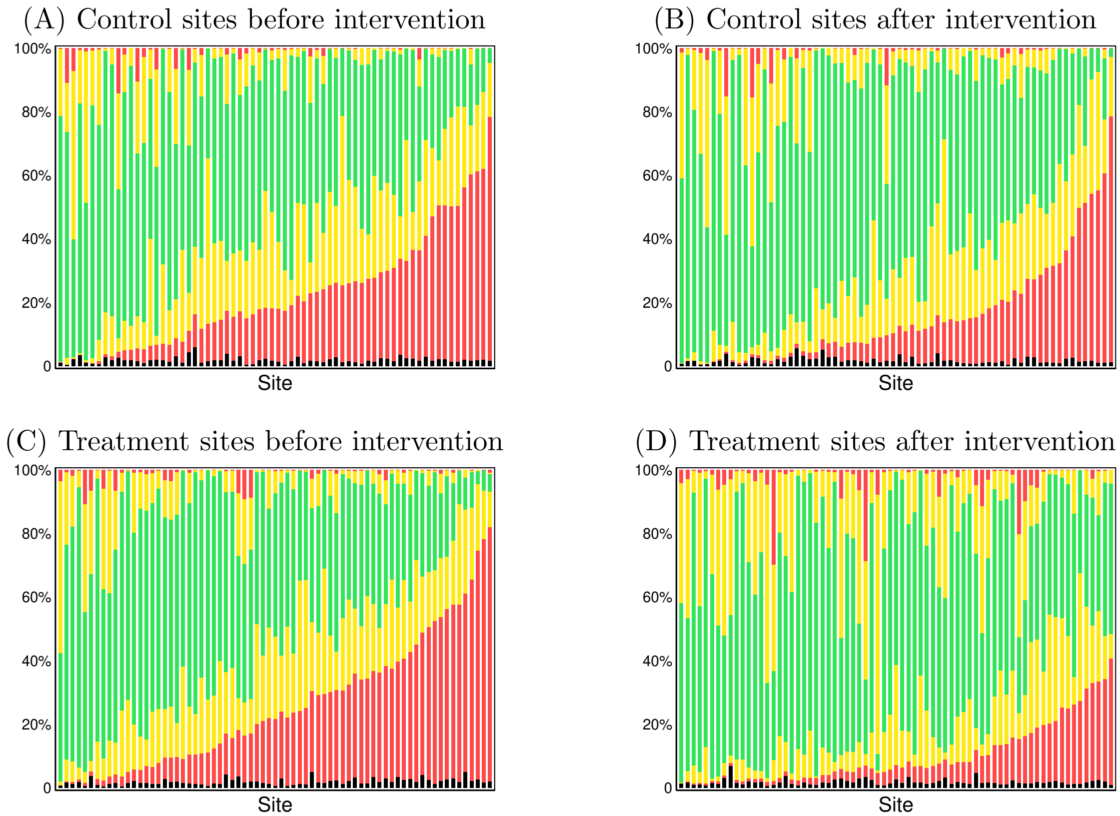
	(1) Minutes power out per hour	(2) Average voltage	(3) Monthly hours in spells w/ voltage >10% below nominal	(4) Monthly hours in spells w/ voltage >20% below nominal
During construction	0.21***	0.76	7.27	5.05
	(0.07)	(1.09)	(8.77)	(7.42)
Treat X During	-0.06	2.38	-21.63	-20.92*
	(0.12)	(1.60)	(13.52)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

This table shows the difference-in-difference results for the impact of the transformer injection treatment on five measures of electricity reliability and quality, measured by GridWatch devices in each site. Columns 1-3 use hourly data while Columns 4-5 use monthly data, all at the GridWatch device level. Standard errors are clustered at the site level. Table C3 shows results for additional voltage quality outcomes at the hourly level and Table C4 show results for additional outcomes at the monthly level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Columns (1) and (2) use data at the hourly level to estimate the impact of line bifurcation on minutes of power outages and on average voltage, controlling for hour of day and week of year

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

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



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

fixed effects.[24] Even though the investment's primary goal—as reflected in MCC's cost-benefit calculations—was to reduce power outages, we find that the transformer injection intervention had no impact on power outages. But as indicated by Figure 4, the treatment increased average voltage by 5.5V relative to control sites. Columns (3) and (4) use monthly data to estimate the impact of the intervention on total time spent in low-voltage spells (periods during which voltage drops at least 10% below the nominal level), and include month of year fixed effects.[25] The treatment caused a 37 (28) hour decrease in the monthly hours of spells with voltage more than 10 (20) percent below nominal, respectively. This represents a 51% decrease in the most severe low-voltage spells that are most likely to damage appliances or limit their functionality.

Figure 5 illustrates the effect of the intervention on voltage quality across the full distribution of treatment and control sites. Green areas indicate the fraction of time electricity fell within ±5% of nominal voltage on average during the pre-construction period, by site. Yellow areas below (above) the green areas indicate deviations of between 5–10% below (above) nominal voltage. Red areas

[24] Results are similar in alternative specifications considering ways in which transformer injection implementation deviated from initial plans (Table C5, Table C6).

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

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.

In line with columns (3) and (4) and Table 4, the main effect of the intervention was to reduce the time where voltage was more than 10% below nominal voltage, though average time between 5-10% below nominal also fell. It also increased the amount of time when voltage was more than 5% *above* nominal voltage—however, as discussed in Subsection 2.1, small deviations above nominal voltage are unlikely to negatively affect appliances. The increase in average voltage thus largely protects customers from voltage sags most likely to damage appliances and affect use.

Columns (2) through (4) of Table 4, and Panels (A) and (B) of Figure 5, show that control sites also experienced improvements in voltage quality over our study period, though these are more modest than the improvements at treatment sites.[26] These improvements do not appear to be due to spatial spillovers from nearby treatment sites: the voltage improvement at control sites does not differ significantly by distance to the nearest treatment site (Table A2). Furthermore, line bifurcation did not significantly change distances to the nearest transformer in control sites for 95% of customers (Panel C of Figure A9). Combining changes in control device distances to the five nearest transformers at endline with how those distances correlate with average voltage suggests this would only explain a small share of the control site increase in voltage post-construction. Voltage improvements in control sites may be due to other large-scale MCC investments in the grid at the time, or to changes in electricity consumption due to COVID-19 or other economic forces.

We break down the impact of line bifurcation on a variety of other measures of voltage quality in the Appendix (Table C3 and Table C4). Briefly, line bifurcation decreases the likelihood that voltage decreases beyond 20% of nominal voltage in a given hour by 4 percentage points (50% relative to the control mean); time spent below this threshold falls by 1.4 minutes per hour (51%). Time spent between 10–20% below nominal voltage decreases by 4 minutes per hour in treatment sites relative to control sites (44%). The number of low-voltage spells per month falls by 46 in treatment sites relative to control sites, a 25% decrease relative to the pre-construction control mean. Relative impacts are again largest for the most severe spells. These effects translate into a reduction in the average severity of low-voltage spells in treatment sites post-construction relative to control sites: the longest spell in a month is 4.5 hours shorter and mean voltage during low-voltage spells is 14V higher. These results show that line bifurcation caused voltage improvements at both the extensive and the intensive margin.

[26] Figure A8 Panel A illustrates the change over time, showing mean voltage level by site treatment status by month.

5.4 Results: Impacts on customers' electricity experiences

We estimate impacts of the line bifurcation treatment on self-reported electricity customer outcomes using the following difference-in-differences specification:[27]

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

Y_{it} is an outcome experienced by respondent i at time t. β_3 captures the primary treatment effect of interest, the differential outcome being observed post-construction in treatment sites. $\boldsymbol{X_i}$ are controls for respondent characteristics, which include age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is a household or a business, and district fixed effects. Standard errors are clustered by site in all regressions.

Figure 6 presents the estimated coefficients for *Post* and *Treat X Post* on primary outcomes normalized around the baseline control mean (Table A3 shows the results for original outcome units). We pool businesses and households for outcomes that are not business- or household-specific.[28]

We estimate a 0.1 SD reduction (p=0.089) 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—for respondents in treatment sites relative to those in control sites. The point estimates for the two components are not individually statistically significant but are both negative, and imply a decrease of 20% in voltage-related damages. While these impacts align with the increase in average voltage measured by GridWatch devices at treatment sites, we do not observe any significant differences by treatment status in customers' self-reported hours of bad voltage over the previous month or in their willingness to pay (WTP) for improved electricity connections.

One potential explanation is that the treatment difference in voltage had decreased somewhat by the time of the endline survey in July–September 2022 (Figure A8), but differences in voltage quality over the previous year were sufficient to reduce appliance damages. Another possible explanation for the non-significant differential impact of treatment on perceived voltage quality is that the improved voltage at all sites between baseline and endline (Figure 4) was sufficient to resolve the majority of voltage issues observable to customers. The decrease in self-reported monthly bad voltage hours in control sites is so large as to drive reported daily hours of bad voltage to nearly zero (Table A3).[29] Seventy-one percent of respondents at endline say voltage is much better than

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

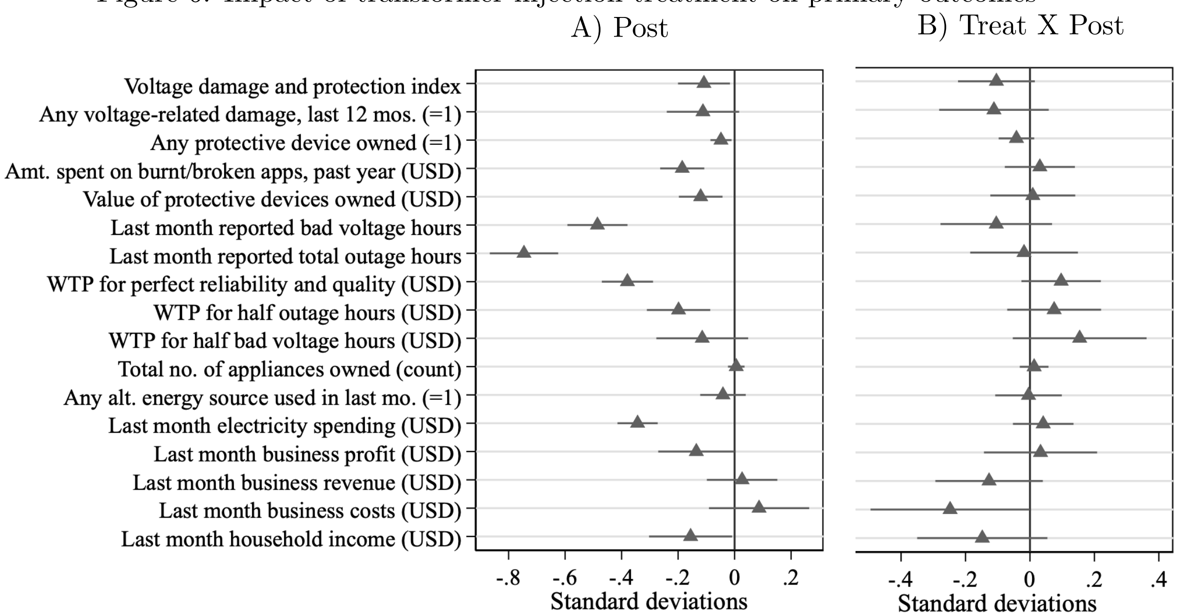
[28]Results are qualitatively unchanged when restricting the sample to businesses only (Table C10). Results and discussion for all other outcomes listed in the pre-analysis plan are included in Appendix D.

[29]This is consistent with seasonal trends in average voltage levels: voltage is typically better in July-September, which coincides with the endline survey (Panel A of Figure A8). We would therefore not expect much difference in self-reported bad voltage hours by site status during these months from a 5V increase in average voltage in treatment sites, even if differences could emerge in other months. Similar seasonal trends explain a large decrease in self-reported outage hours between baseline and endline in control sites, which is not consistent with the non-significant effect of construction on outage hours as measured using GridWatch devices.

two years ago, along with 19% saying it is slightly better. Businesses are also 19 percentage points less likely to say bad voltage is an obstacle to business operations at endline compared to baseline.

Across control and treatment sites, households and businesses report improvements in electricity quality and significant decreases in voltage damages, costs, and protective devices after the construction period (Figure 6 Panel A). This is consistent with the increase in voltage in control sites post-construction but cannot be attributed to the line bifurcation intervention. WTP for improved electricity connections also falls on average in the post period, which likely reflects both the improvements in voltage and seasonal differences in outage hours between the baseline and endline surveys. Use of alternative energy sources such as generators and solar panels was low at baseline and did not change over time, consistent with no changes in outages as measured by GridWatch devices.

Figure 6: Impact of transformer injection treatment on primary outcomes



Coefficients and 95% confidence intervals from difference-in-differences regressions of the impact of the transformer injection intervention on normalized outcomes. Units for all outcomes are standard deviations relative to the baseline control mean. The estimated impacts for non-normalized versions of the outcomes are shown in Table A3. Profit, revenue, and costs are measured for businesses only. Household income is measured for households only. All other outcomes pool businesses and households. The voltage damage and protection index is a normalized sum of normalized versions of the any voltage-related damage and any protective device owned outcomes.

5.5 Results: Impact on socioeconomic outcomes

We estimate the impact of the transformer injection intervention on a variety of household and business socioeconomic outcomes using Equation 2. The results in Figure 6 (Panel B) show no effect of the intervention on appliance ownership or electricity spending. The large average decrease in electricity spending in the Post period (Panel A) partly reflects seasonal differences in electricity use: the baseline survey took place during the hot season in Accra when use of cooling appliances is higher while the endline survey occurred later.

We observe a significant reduction in business expenditures in the past month of 0.22 SD (USD 98, $p = 0.049$) post-construction in treatment sites relative to control sites, however we also see a modest reduction in reported revenues of 0.14 SD (USD 87, $p = 0.14$), such that we see no aggregate effect on profit. We do not find statistically significant impacts of the intervention on a variety of other business variables (Table A4), and the effects on business costs do not survive False Discovery Rate (FDR) adjustment for multiple hypothesis testing (Table C7). We therefore attribute this result to statistical noise.

We also find no statistically significant impact of the intervention on monthly household income or on a range of household-specific outcomes (Table D6), including facing health challenges due to reliability issues, sources of light for studying and reading, the share of household adults with paid jobs, and safety in the area. Taken together, these results suggest that the investment did not sufficiently increase power quality at treatment sites relative to control sites to have a detectable impact on socioeconomic outcomes.

In contrast, we find that many outcomes changed significantly in control sites over the period from the baseline survey in March-April 2021 to the endline survey in July-September 2022 (Figure 6 Panel A). Post effects largely remain significant after FDR adjustment (Table C7). Part of this change may be due to reduced concerns and restrictions related to the COVID-19 pandemic, or seasonal differences in energy use and economic activity due to the differences in the timing of the two surveys. Average monthly business profits, household incomes, and electricity spending also fall in USD terms. This is partly due to high levels of inflation in Ghana at endline relative to baseline, and may also reflect seasonality in economic activity.

What can explain the modest socioeconomic impacts of the line bifurcation intervention? One factor is that improvements in voltage caused by the intervention coincide with broader voltage quality improvements across the study area, potentially reducing impacts on treatment site socioeconomic outcomes. Many of the changes in outcomes we observe in the post-construction period are consistent with impacts driven by the broad improvements in electricity quality measured by GridWatch devices. The probability of having had an appliance damaged by voltage issues, ownership of voltage protective devices, and WTP for improved electricity connections all fall post-construction. It is therefore possible that the improvement in voltage that control sites experienced after line bifurcation was just enough to cause improvements in socioeconomic outcomes, such that there was no additional benefit of the additional improvements in voltage that treatment sites experienced relative to control sites.

Another contributor may be that chronically low-quality and unreliable electricity causes customers to have a limited stock of electric appliances, such that customers only benefit from improved voltage after they increase or improve their stock of appliances. At baseline the median respondent owned 3 different types of electric appliances along with light bulbs. We observe no difference in appliance acquisition after construction by treatment status: 37% of respondents at endline reported acquiring at least one new appliance since the baseline survey, with no difference between businesses and households or between control and treatment sites (Figure A11). Many of these appliances replaced others already held such that the mean total count of electric appliances did not change significantly between baseline and endline.

5.6 Heterogeneous effects

In this section we perform a set of heterogeneity analyses using different subsets of our sample to test two other possible explanations for the null socioeconomic effects of the intervention.

First, it is possible that the baseline levels of voltage were within the acceptable range such that any improvements in voltage due to line bifurcation were not salient to the respondents. To test this hypothesis, we estimate the impact of transformer injection on socioeconomic outcomes by baseline voltage quality. We divide the sample by whether respondents were above or below the median daily hours of voltage within 10% of nominal average voltage level (20.3 hours). We find no statistical differences in the impact of line bifurcation on socioeconomic outcomes by baseline voltage quality (Table A5 Column 1), despite the fact that the increase in average voltage as measured by GridWatch devices was larger in treatment sites with below-median baseline voltage (Table A6). We estimate that line bifurcation caused a bigger decrease in reported hours of bad voltage in past month for respondents with worse baseline voltage relative to those with better baseline voltage, but the difference is not statistically significant.

Next, voltage improvements might only be salient to respondents who are more likely to rely on electricity. We consider the impact of line bifurcation by a set of baseline characteristics that reflect the importance of voltage quality for respondents, including reported electricity importance (for businesses), willingness to pay for perfect electricity reliability and quality, and ownership of protective devices. Again, we find no significant differences in the impact of the transformer injection intervention on socioeconomic outcomes for groups with higher values of these metrics (Table A5 Columns 2-4).

The modest improvements in voltage quality due to transformer injection thus have no impact on socioeconomic outcomes regardless of their baseline voltage experiences and of how important electricity is to them according to their baseline responses.

5.7 Robustness

We test the sensitivity of the impacts on average voltage and outage hours to different measures of where and when planned transformer construction was completed (Table C5 and Table C6). We drop two treatment sites where the contractor indicated that the transformer was not commissioned and drop additional treatment sites where additional construction monitoring found no new transformer constructed. We also run an instrumental variables version of this regression, using treatment assignment as an instrument for new transformer construction. We run the same sensitivity checks for socioeconomic impacts of the treatment (Table C8). To address any potential SUTVA violations, we drop control sites closer to treatment sites than median (1.3km) (Table C11). We also drop 'movers'; that is, anyone for whom the monotonicity assumption on distance to the nearest transformer is violated (not shown). None of these robustness tests qualitatively change the results (Section 6).

We use alternative specifications aiming to directly measure the association between changes in voltage quality and primary outcomes (Table C9). We find that improving voltage quality is associated with significant reductions in WTP for improved electricity connections, in the probability that any appliance is damaged by voltage issues, and in the value of protective devices owned. We find no significant effects on other outcomes. Voltage improvements thus appear to have limited impacts on outcomes not directly linked to voltage quality. These results indicate that larger voltage quality improvements may not lead to more meaningful impacts on socioeconomic outcomes. However, this may be a function of the range of average voltage over which we are estimating these effects. The impacts of average voltage are likely to be non-linear, with larger marginal effects for increases at low levels of voltage that for increases closer to the nominal voltage level.

5.8 Cost–benefit analysis

MCC spent approximately $14 million on low voltage (LV) line bifurcation in the Achimota, Dansoman, and Kaneshie districts of Accra, Ghana, which have an estimated combined population of around 49,000 households (GSS, 2014). How does this compare to the benefits identified above?

First, we use stated willingness to pay (described in Subsection 4.3) as an estimate of value. The investments generated no outage improvements, but significantly cut down voltage problems. Assume the investments generate perfect voltage quality but do not reduce outages. An upper bound for the value to consumers is the respondents' WTP for a connection with perfect voltage quality and half their current outages. Customers report being willing to pay at most an additional USD 1.64 per month for such an improvement, or USD 19.7 per year. Assuming a new transformer generates 30 years of usage (with an annual discount rate of $\delta = 0.95$), this yields aggregate benefits of USD 280 per household, or USD 13.7 million across the 49,000 households in the three districts. This is a simple back of the envelope calculation—it could be an underestimate (WTP may underestimate value if respondents are constrained, we do not include the population of businesses) or an overestimate (the investments did not generate perfect voltage quality or reduce outages, and improvements vary across sites in the 3 districts)—but may approximate the likely cost-benefit ratio.

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

These results under different assumptions suggest that the benefit-cost ratio of this intervention is unlikely to exceed one, which is not surprising given the lack of impacts beyond immediate voltage-related outcomes.

6 Discussion and Conclusion

In this paper, we use new high-frequency power quality measurements to present the first detailed analysis of challenges with voltage quality in a developing country context. While bad voltage quality can damage and limit the functionality of electric appliances, little attention has been given to it in policy documents due to data limitations of measuring both the severity of voltage problems and the impact on households and businesses.

We address constraints to availability of power quality data by deploying sensors across Accra, Ghana, and show that poor voltage quality is a pervasive problem that creates costs for electricity customers. On average, the median customer experienced 16 hours of low voltage and 10 hours of power outages per month between March 2019 and November 2020, as measured by GridWatch devices, and survey respondents self-reports of bad voltage and outage hours are closely correlated with these measures. Our sensors data show that there are widespread voltage problems in Accra, whereby approximately 20% of grid electricity is of poor quality, i.e., was more than 10% below the nominal level of 230V.

Importantly, bad voltage is costly for customers: we show that 26% of households and businesses spend \$51 and \$39 on equipment to protect their appliances against voltage problems and on the repair of burnt or broken appliances, respectively. In addition, one-third of businesses state that voltage quality is a very important obstacle to their operations. Households and businesses are willing to pay similar amounts for electricity connections with reduced outages and with improved voltage, and they assign such improvements a similar share of hypothetical public investment, indicating that electricity quality imposes similar costs on customers as electricity reliability.

Next, we use a difference-in-differences design to estimate the impact of an intervention, which entailed adding new transformers to the electricity grid to "reduce the length of LV circuits and improve service quality", on voltage quality and socioeconomic outcomes. We show that the intervention is successful in terms of improving voltage quality: adding a new transformer increases average voltage by 5V and decreases the time spent with low quality voltage by 37 hours in treatment sites relative to control sites. These improvements caused a modest reduction in the ownership of protective devices and subsequent voltage-related damages, but they had no impact on major household and businesses outcomes, including electricity spending, appliance ownership, business profits, and household income.

Several factors could explain the lack of economic impacts of the transformer construction intervention. First, to realize economic benefits from improved voltage, customers would need to invest in increased appliance ownership and use. Such investment may have been suppressed following economic effects of the COVID-19 pandemic. Customers may also not have had sufficient time to observe voltage improvements and respond to them, or may not have trusted the quality gains would persist. The study sample also largely includes less wealthy households and micro businesses which would likely benefit less from better electricity quality than households and businesses with more appliances and electricity use.

Second, power quality improved significantly in control sites over the study period, making additional improvements in treatment sites less important in terms of the voltage experience as voltage increases above a certain threshold do not affect appliance performance. The timing of the endline survey may have contributed to this as it coincided with a period of the year when electricity quality is typically better due to reduced load. The marginal improvement in voltage quality in treatment sites may be more consequential for socioeconomic outcomes during months with worse overall voltage.

Third, while average voltage improved as a result of transformer construction, voltage issues were not completely resolved. Voltage sags, including large and lengthy drops in voltage remain common post-construction and voltage spikes following outages were not addressed by the intervention. Customers therefore still face a threat from bad voltage. Future research should seek to identify impacts of larger improvements in power quality over longer time frames to determine whether moving closer to the norm in high-income countries generates larger economic effects.

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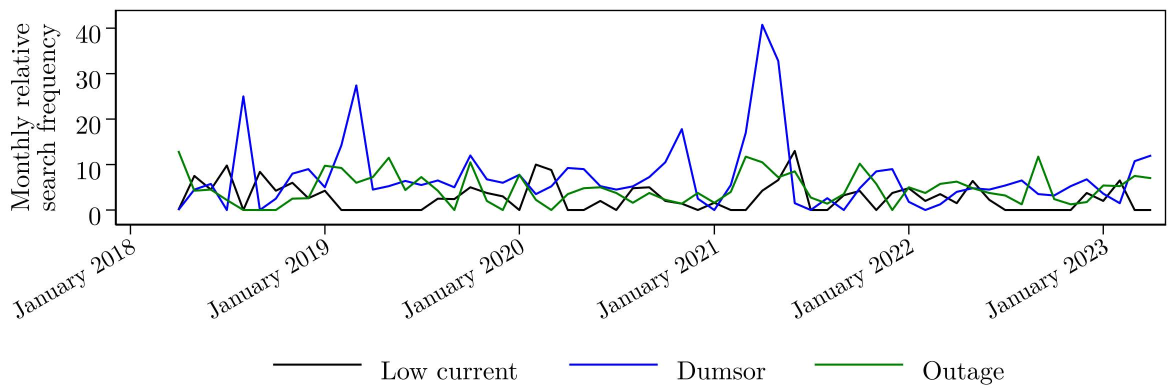
Appendix Figures

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

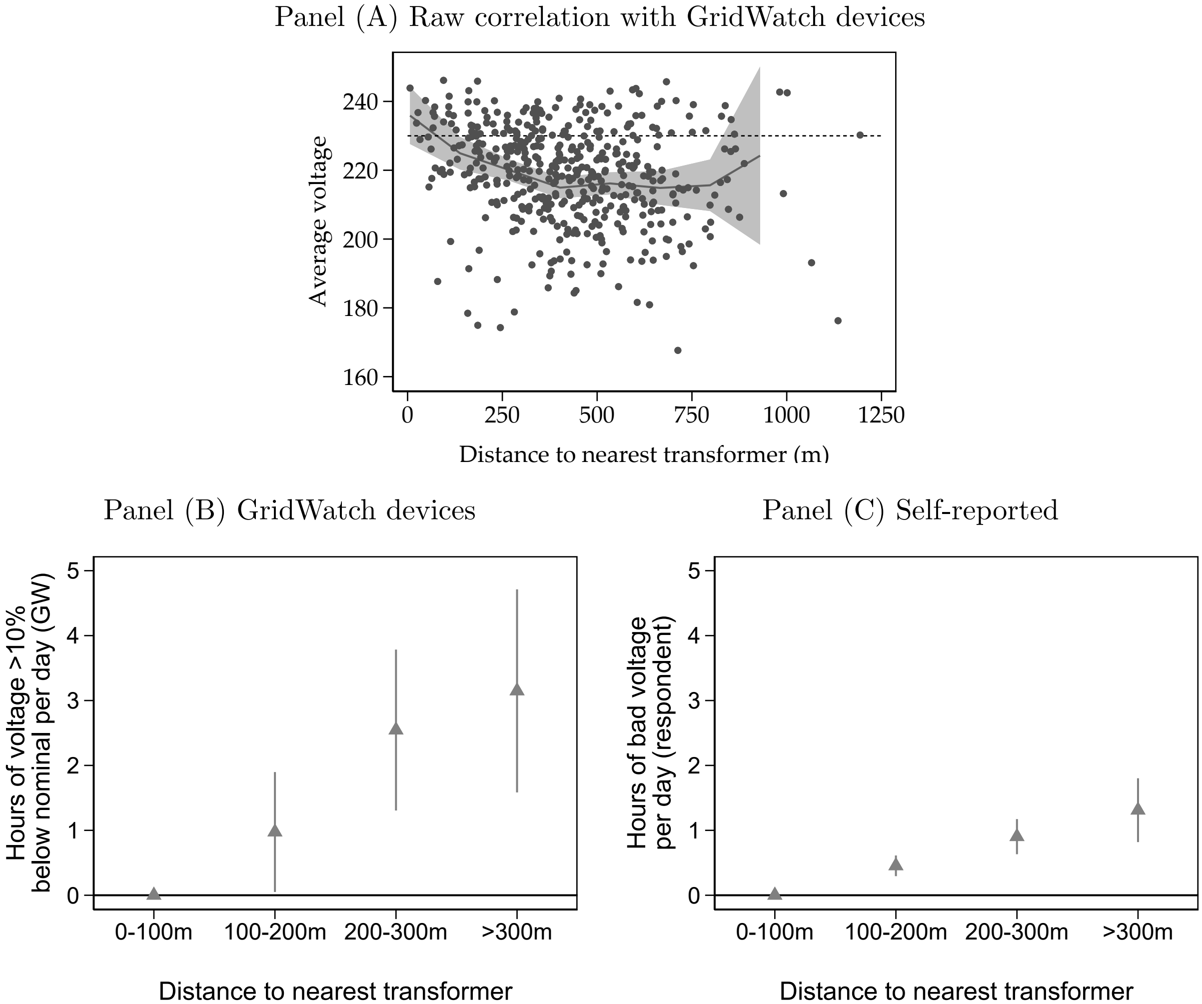


Data are aggregated from weekly Google Trends data for the specified search terms. Relative search frequency is calibrated to the maximum search interest across the three terms over the time period. “Low current” is the most common phrase used in Ghana to refer to issues related to voltage. “Dumsor”,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

Figure A2: A GridWatch device

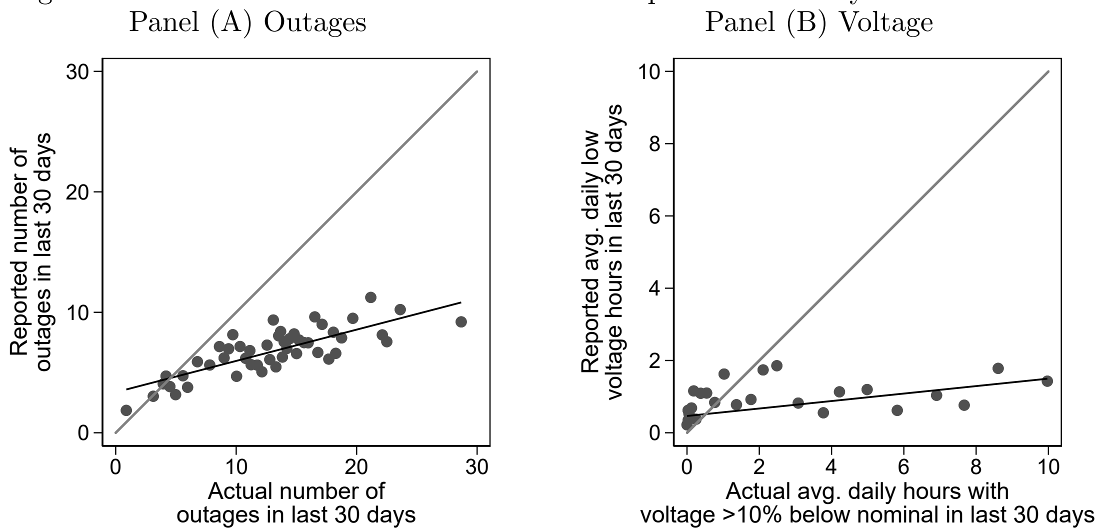
A GridWatch device, part of nLine’s GridWatch technologies used to measure power outages and voltage. Each GridWatch device measures voltage in real-time, stores this on a local SD card, and sends the data to the cloud via a sim card whenever local cellular service permits. A back-end computing technology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

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



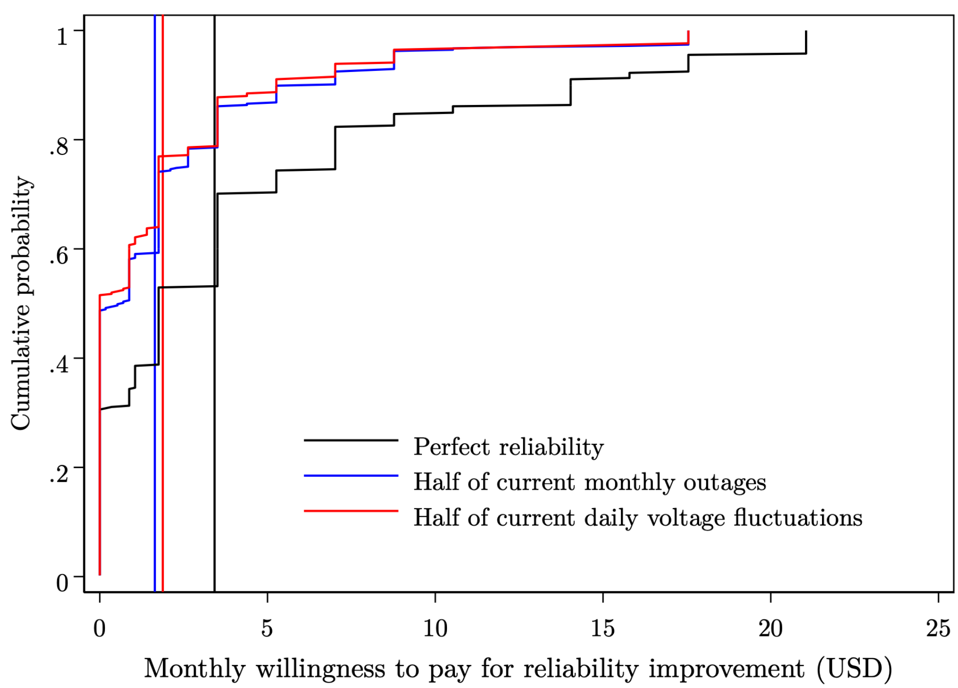
Panel A shows device-level average voltage by the distance along the electricity network from that device to the nearest transformer using GridWatch data from Ghana (described in Section 3). The black line shows the best fit from a local polynomial, and the shading show a 95% confidence band. For Panel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

Figure A4: Correlations between measured and reported electricity characteristics



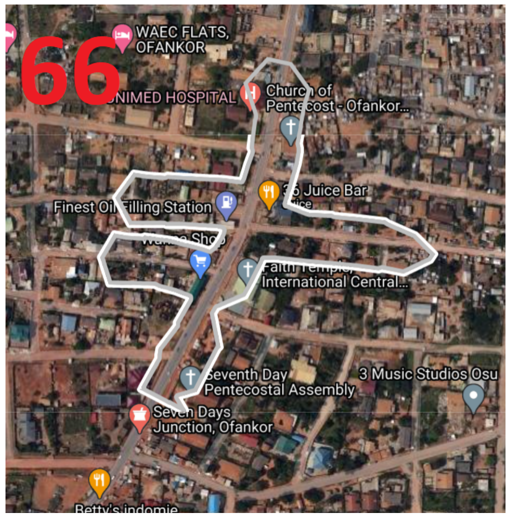
Respondents are asked about average daily 'bad' voltage hours and about the count of outages over the 30 days preceding the survey. Respondents are matched with GridWatch data from the device that is nearest to their location. Voltage more than 10% below nominal is used as a proxy for 'bad' voltage as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

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



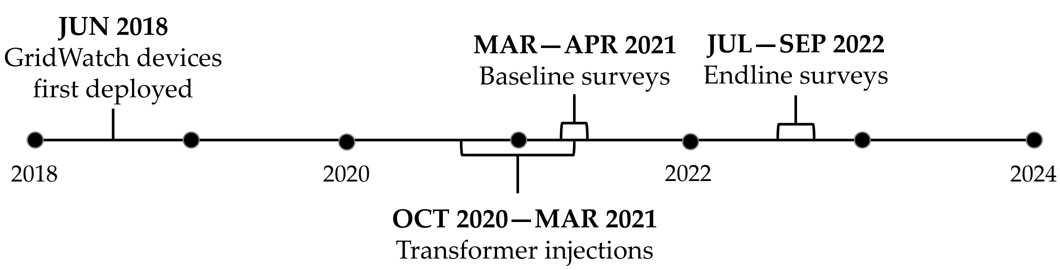
Willingness to pay is elicited first for connections with perfectly reliable electricity, and is then elicited for connections with specific reliability improvements. Vertical lines indicate the mean willingness to pay for each type of improved electricity connection. The mean monthly electricity spending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

Figure A6: Example of a surveyed site



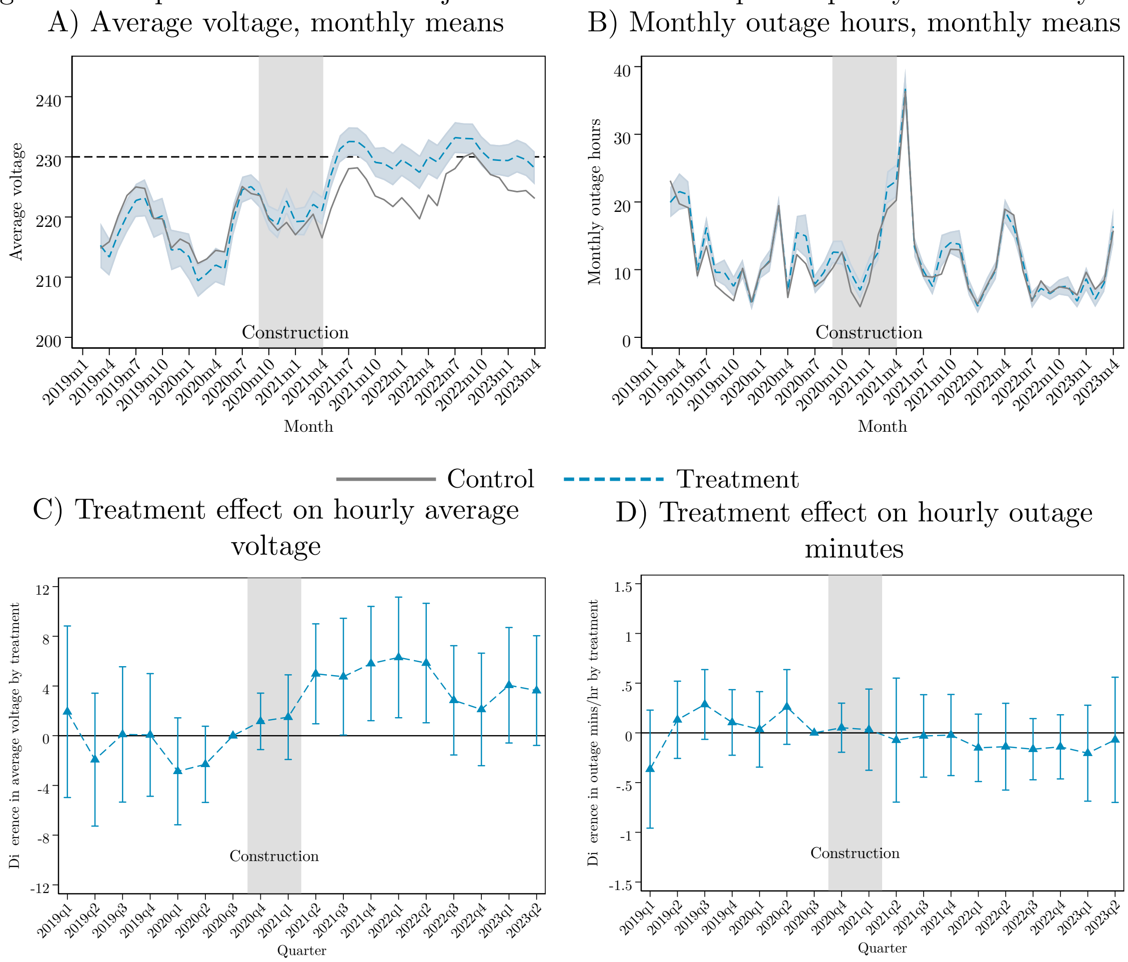
A sample site map where field officers conducted surveying. The outline in gray denotes the area within 200 meters of the proposed injection site and at least 300 meters from an existing transformer along the electricity network.

Figure A7: Project timeline



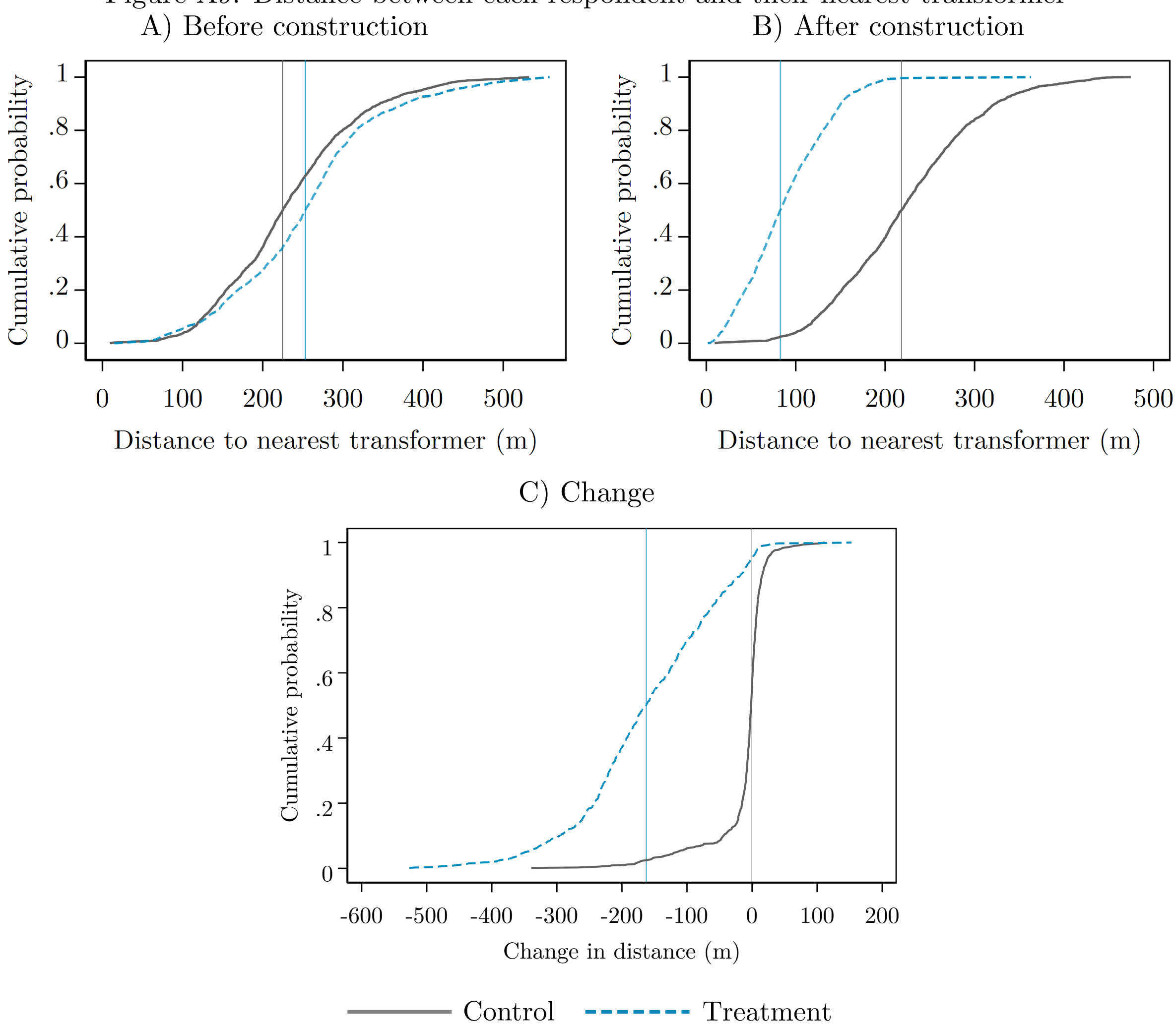
Timeline of research and construction activities. GridWatch data were collected continuously in the months after device deployment. The analyses in this paper include GridWatch data collected through April 2023.

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



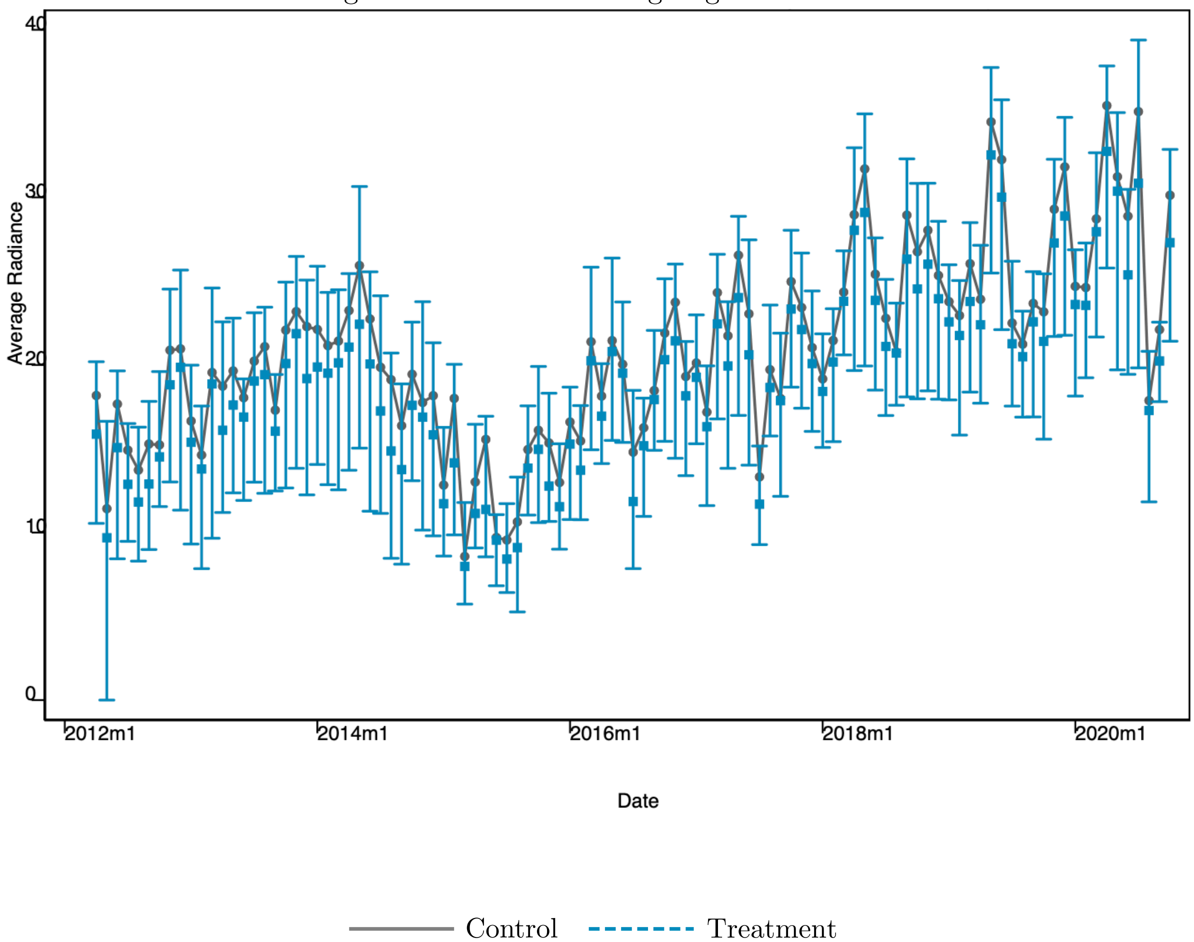
Panels A and B show monthly mean values by site treatment status calculated by taking mean average voltage and sum of outage minutes across hours within a month by GridWatch device, and then taking means of these variables across devices within a month by treatment status. Bars on the means for treatment sites are 95% confidence intervals. Panels C and D show estimated coefficients and 95% confidence intervals from a regression of outcomes on site treatment status by quarter, controlling for hour of day, week of year, and site fixed effects. The reference quarter is 2020Q3, before the start of the construction period. Standard errors clustered at the site level.

Figure A9: Distance between each respondent and their nearest transformer



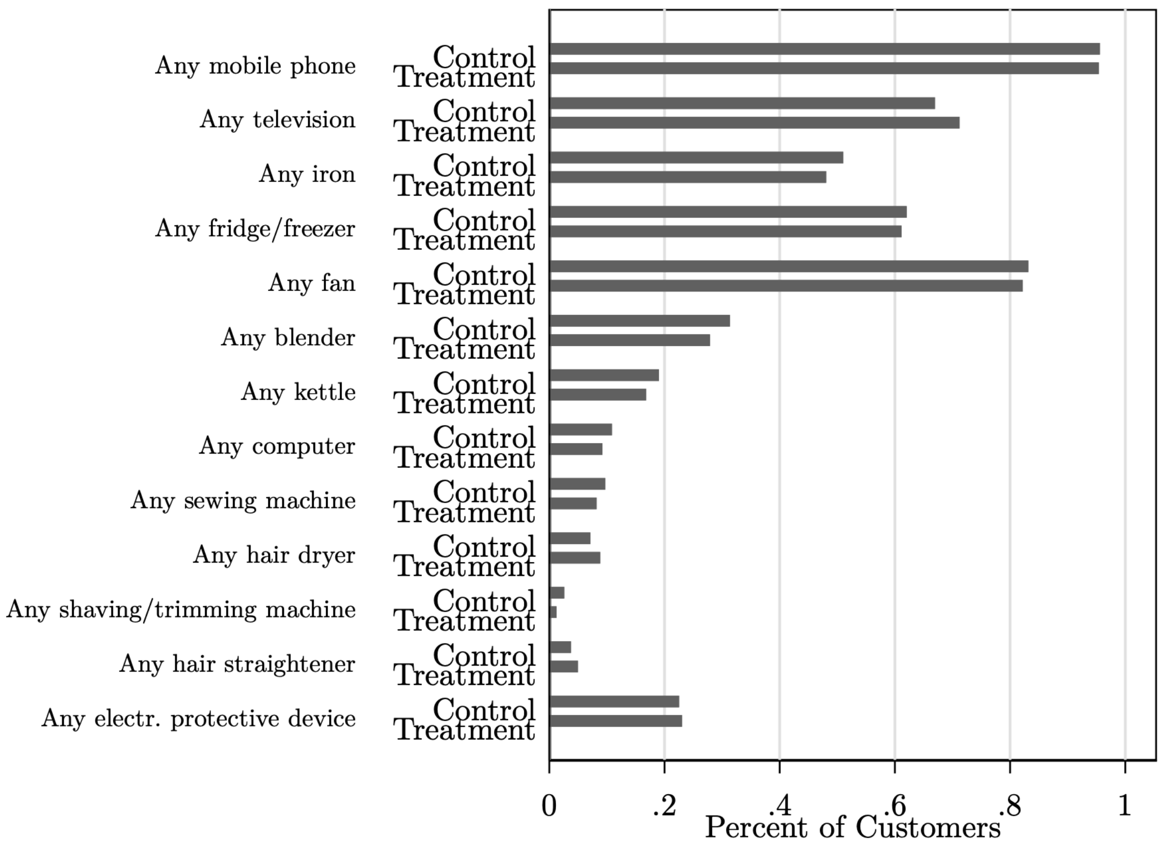
The figures show distance to the nearest transformer in meters at baseline to endline for survey respondents, as well as the change in this distance from baseline to endline. Vertical lines mark the median respondents in control and treatment sites.

Figure A10: Balance in nightlight radiance



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

Figure A11: Appliance acquisition between surveys by site treatment status



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

Appendix Tables

Table A1: Baseline balance by site status

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

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

Table A2: Testing voltage spillovers in control sites from transformer injection intervention

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

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

Table A3: Impact of transformer injection intervention on customer electricity experience

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

Notes: This table shows the difference-in-difference results from the Equation 2 pooling businesses and households. Each row represents an outcome. All outcomes pre-specified in the pre-analysis plan (Berkouwer et al., 2019). All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Results are qualitatively unchanged when using logged versions of continuous outcomes. Sample sizes vary for some questions because of missing data, particularly when respondents were unable to estimate monetary values with a high degree of confidence, or because some questions were only asked to a subset of respondents. Reliability outcomes are measured using respondent self-reports based on the 30 days prior to the survey date at both baseline and endline. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is a household or a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sharpened FDR q-values following Anderson (2008) are shown in Table C7. All effects of Post remain statistically significant after this adjustment, but the significant effects of Post × Treat do not.

Table A4: Impact of transformer injection intervention on main business outcomes

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

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

Table A5: Heterogeneous impacts of transformer injection intervention on primary outcomes

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

Notes: This table shows the heterogeneous treatment estimates by (1) baseline average dailxy hours with good voltage (2) electricity importance at baseline (3) baseline WTP for perfect reliability and (4) baseline count of voltage defensive investment. In column (1), "below median" is a dummy variable for those that are below the median in terms of average number of hours of good voltage quality at baseline. In column (2), a firm is classified as "high importance" if the owner reported that electricity is "very important" or "extremely important" when they were asked about the importance of electricity as an obstacle at baseline. In column (3), a firm is classified as "high WTP" if their WTP for perfect reliability is greater than or equal to the 50th percentile. In column (4), "High" refers to firms that report having at least 1 defensive investment at baseline. We estimate a coefficient for each of the four groups, using the following equation: Y_{it}=α_0 + α_1 $Group * Treat * Post_{it}$ + α_2 $Group * Treat_{it}$ + α_3 $Group * Post_{it}$ + α_4 $Post * Treat_{it}$+ α_5 $Post_t$ + α_6 $Treat_i$ + α_7 $Group_i$ +u_{it}; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A6: Impacts of transformer injection intervention on voltage by baseline voltage quality

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

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

Appendix C: Robustness checks

Table C1: Balance between panel and attrited respondents

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

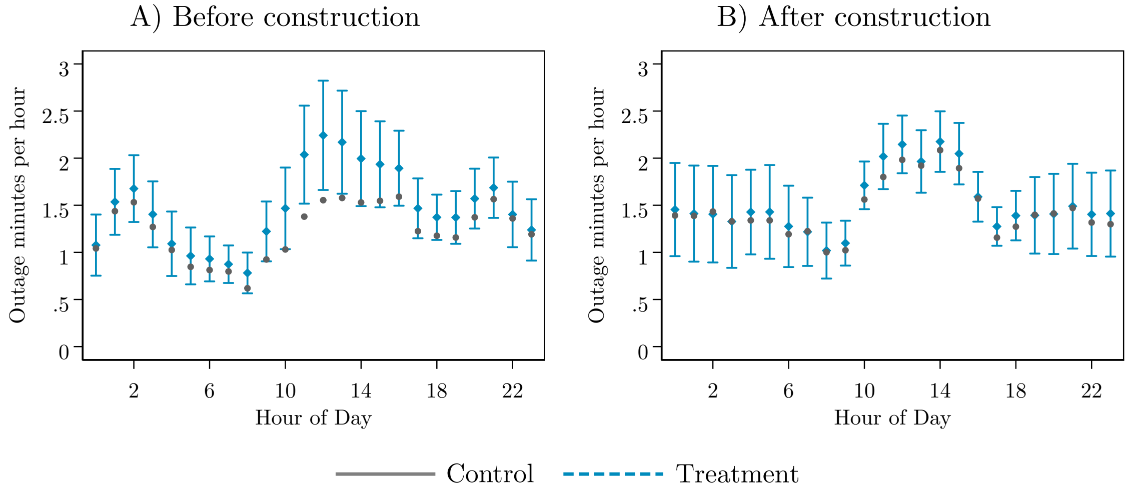
Notes: This table shows means in the baseline period for survey respondents, pooling businesses and households, and tests for significance of the differences in means by whether the respondent was also surveyed at the endline. The p-value for the joint F-test for household baseline characteristics is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

Table C2: Correlation between attrited respondents' characteristics and treatment status

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

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

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



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

Table C3: Impacts of transformer injection intervention on additional voltage quality measures, hourly data

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

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

Table C4: Impacts of transformer injection intervention on additional voltage quality measures, monthly data

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

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

Table C5: Impact of transformer injection intervention on hourly average voltage, robustness to implementation issues

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

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

Table C6: Impact of transformer injection intervention on hourly outage minutes, robustness to implementation issues

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

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

Table C7: Impact of transformer injection intervention on primary outcomes

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

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

Table C8: Impact of transformer injection intervention on primary outcomes, accounting for implementation issues and construction timing

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

This table shows the same difference-in-difference analyses presented in Table A3. Column 1 replicates the 'Post × Treat' column from Table A3. Column 2 drops two sites in Kaneshie where the construction manager SMEC indicated the new transformer was not commissioned successfully. Column 3 drops sites where our own construction monitoring activities indicated no new transformer was built in a treatment site or a new transformer was built in a control site. Column 4 instruments for observing a new transformer during the construction monitoring visits with site treatment assignment. Column 5 shows the difference-in-difference results from the main equation, by dropping geographically close control sites. We define distance by the shortest path to a treatment site, and we drop ant control site that is within 1.3 km from a treatment site, where 1.3 km is the median distance to a treatment site. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C9: Correlations between voltage quality and primary outcomes

	N	Control Mean (SD)	Avg voltage (SE)	Hours below nominal-10 (SE)
Reported hours of bad voltage in past month	3130	43.05	-0.01***	0.03***
		[87.25]	(0.00)	(0.01)
Reported total outage hours in past month	3092	32.20	-0.01***	0.02***
		[31.09]	(0.00)	(0.01)
Max monthly WTP for perfect reliability	3150	3.62	-0.01***	0.01***
		[4.85]	(0.00)	(0.00)
Max monthly WTP for half of curr. outages	3150	1.74	-0.00***	0.01**
		[2.98]	(0.00)	(0.00)
Max monthly WTP for half of curr. volt. fluc.	2000	2.14	-0.00**	0.01
		[3.68]	(0.00)	(0.01)
Voltage damage and protection index	3150	0.00	-0.00*	0.01**
		[1.00]	(0.00)	(0.00)
Any appliance damaged by voltage in past year	3150	0.25	-0.00**	0.01**
		[0.43]	(0.00)	(0.00)
Amt spent on burnt/broken apps in past year	3080	10.22	-0.00**	0.01*
		[37.23]	(0.00)	(0.00)
Any voltage protective devices	3150	0.25	-0.00	0.00
		[0.44]	(0.00)	(0.00)
Value of voltage protective devices	2668	6.05	-0.00	0.01*
		[25.51]	(0.00)	(0.00)
Uses an alternative energy source	3150	0.05	0.00	-0.00
		[0.22]	(0.00)	(0.00)
Total number of appliances	3150	8.59	0.00	-0.00
		[5.98]	(0.00)	(0.00)
Monthly electricity spending	3050	19.51	-0.00	0.01
		[18.67]	(0.00)	(0.00)
Total profit in past month	1104	108.61	-0.00	-0.00
		[158.44]	(0.00)	(0.00)
Total revenue in past month	1280	436.45	0.00	-0.01
		[689.48]	(0.00)	(0.00)
Total monthly reported business spending	1206	304.41	0.00	-0.01
		[395.39]	(0.00)	(0.00)
Total household monthly income	1358	360.69	-0.00	0.01*
		[491.13	(0.00)	(0.01)

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

Table C10: Impact of transformer injection intervention on primary outcomes for businesses

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

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

Table C11: Impact of transformer injection intervention on main business outcomes, dropping geographically close control sites

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

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

Appendix D: Pre-specified analyses of socioeconomic outcomes

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

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

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

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

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

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

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

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

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

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

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

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

Table D5: Impact of transformer injection intervention on business outcomes

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

Notes: This table shows the difference-in-difference results from the main equation. Each row represents an outcome. All variables measuring values are in USD; 1 USD≈5.8 GHS during the baseline survey and ≈8.5 GHS during the endline survey. Results are qualitatively unchanged when using logged versions of the outcomes. All indices are constructed as the sum of normalized components, and are then normalized to have mean 0 and SD 1 for control businesses in the baseline. We also show results for the index components for completeness. Purchasing alternative energy sources and always using generator during business hours were only measured at endline so were excluded from the permanent response index. The variable moved to a different location is only available for the post period. All the elements of this index are re-scaled such that higher values represent worse outcomes. For example, perceived safety in area can take any value from 1-5, where 5 indicates very unsafe. In all the regressions, we control for respondent age, gender, education, whether the meter is paid directly by the user, number of meter users, whether the respondent is the business owner or a manager, whether the location includes both a household and a business, and district fixed effects. The control mean is the mean for control sites in the baseline period. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table D6: Impact of transformer injection on household outcomes

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

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