Voltage quality and economic activity

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Abstract

We combine state-of-the-art, customer-level power measurements with 2,000 household and business surveys in Accra, Ghana to analyze an under-studied underpinning of most modern economic activity: grid voltage. Voltage problems are ubiquitous: average voltage is 219V, well below nominal (230V). Electricity is 10% below nominal one-fifth of the time, damaging equipment and driving customers to purchase expensive protective equipment. Customers would pay 10% more for electricity to improve voltage quality. Quasi-random grid investments costing $286 per household increase voltage by 5V, protecting appliances but generating no other economic impacts one year later. We provide a framework for evaluating alternative grid investments.

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1 Introduction

Novel sources of spatially and temporally high-frequency data—such as satellite imagery, internet-of-things, and mobile phone records—have massively expanded the scope and precision of economic measurement in recent years. This has enhanced researchers' abilities to assess the technological determinants of economic performance. Within the electricity sector, researchers have used such data to study affordability, pricing, and formality, among other topics.[1] In this paper, we leverage the large-scale collection of spatially and temporally high-frequency power quality measurements to study a core underpinning of modern commercial, industrial, and residential electricity consumption: voltage quality.

The economic implications of poor voltage quality have as of yet received little attention. In most countries, electric utilities are charged with providing electricity within ±10% of targeted voltage—for example, 120 volts (V) in the US and 230V in Ghana—so that machinery and appliances can operate efficiently and without damage (CENELEC, 2006). Utilities in low-resource contexts often fail to meet these standards, but voltage issues continue to be deprioritized in policy and regulatory debates. The United Nations Sustainable Development Goal 7—*"affordable, reliable, sustainable and modern energy for all"*—does not even mention voltage (UN, 2022). World Bank reports often either do not discuss voltage or depend on household self-reports, which—as we discuss in this paper—can be inaccurate (WB, 2020; WB, 2021). The Energy Sector Management Assistance Program Multi-Tier Framework categorizes electricity access and reliability in detail, but only defines two coarse tiers of voltage quality: whether or not voltage problems affect appliance use (ESMAP, 2015).[2] Yet even this imprecise definition of voltage quality is difficult to measure. Understanding the economic costs of poor voltage quality and the value of voltage improvements—in particular relative to improvements in access, reliability, or affordability—is crucial in enabling resource-constrained utilities to optimally target grid investments.

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

The analyses generate three key findings. First, we document significant voltage problems. Average voltage at baseline is 219V, significantly lower than the targeted nominal level of 230V. Voltage is more than 10% (20%) below the nominal level 5.3 (1.2) hours per day. Customers

[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), Guo et al. (2023), Hardy and McCasland (2019), and Migisha et al. (2023).

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

experience an average of 250 'spells' each month—lasting more than 130 hours—when voltage drops at least 10% below nominal for at least two minutes. Such fluctuations can be highly damaging for commercial and residential appliances: machinery cannot operate at full capacity, and protective components can malfunction, damaging appliances.[3]

Second, these voltage issues are salient to respondents and bring economic costs. One-third of businesses report voltage to be an important obstacle to operations. A quarter of respondents own devices to protect appliances against bad voltage, valued at $60 on average (approximately 15% of both monthly household income and monthly business revenues in the sample). Despite such investments, 25% of respondents report that at least one appliance was damaged due to bad voltage in the last year, costing an average of $45 to repair or replace.

Finally, we use a difference-in-differences approach to evaluate the impacts of a voltage quality improvement, comparing outcomes at 76 sites where a new transformer was constructed with 75 comparable sites that did not receive such an investment. The investments increased average voltage by almost 5V and reduced the time spent with low quality voltage by 37 hours per month (with no impact on outage hours). This causes a modest reduction in voltage-related damages and ownership of protective devices. However, it has no significant impact on major household and firm socioeconomic outcomes including electricity spending, appliance ownership, business profits, and household income. This is true across respondents with different baseline levels of voltage quality and electricity dependency.

The investment's $286 cost per household likely exceeds the economic benefits accruing to customers. While the investment may generate benefits for the utility that we do not capture by reducing technical losses and maintenance costs, these savings would have to be very high to have a meaningful impact on the cost-benefit calculation. Governments and other funders may want to re-evaluate investments in voltage quality relative to other investments that may be more impactful.

What can explain the limited socioeconomic impacts? The improvements may not have been sufficient: customers in treatment sites still experience 12 hours per month when voltage is more than 20% below the nominal level, and the intervention likely did not address transient voltage spikes or sags (which our monitoring technology is unable to observe). In addition, investment in new appliances could have been hindered due to the COVID-19 pandemic or not yet realized by the time of the endline survey, one year after the intervention.

These analyses offer a framework to measure the severity of voltage problems and evaluate the impact of power distribution network improvements. Governments and donors face significant constraints and must make strategic decisions on how to allocate scarce resources. Within the electricity sector, one could support grid expansions to communities without connections, generation capacity expansions to support the continuous operation of high-utilization equipment, or distribution network improvements to enhance voltage quality and power reliability. Our empirical analysis provides an important first data point by analyzing the impact of a grid investment on

[3] 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" (p. 576).

voltage and subsequent effects on economic outcomes.

This paper builds on a small set of research papers on voltage quality issues in low- and middle-income countries. Blimpo and Cosgrove-Davies (2019) report that one-third of surveyed enterprises in Tanzania reported appliance damage from voltage fluctuations. In a 2018 survey conducted in Cambodia, Ethiopia, Kenya, Myanmar, Nepal, and Niger, 28% of schools and health centers reported that damaged equipment due to voltage fluctuations was a constraint to operations (WB, 2020). Jacome et al. (2019) directly measure voltage levels among 25 households in rural Tanzania and find that average voltage is often more than 10% below nominal. 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. More broadly, this paper expands our understanding of the economic impacts of infrastructure quality in low- and middle-income countries (Gertler et al., 2022; WB, 2019; WB, 2019).

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

2 Voltage quality: importance and measurement challenges

Existing global energy policy focuses overwhelmingly on access and reliability. The World Bank quantifies these dimensions in nuanced detail, delineating 12 distinct categories of capacity and 10 categories of availability, with detailed metrics for each category (ESMAP, 2015). However, voltage is only characterized by two categories: "voltage problems that damage appliances" and "voltage problems do not affect the use of desired appliances". This very coarse categorization of what is a highly complex phenomenon may be driven by limited data availability on voltage. Without granular data, voltage quality cannot be adequately factored into grid planning or tracked using development indicators.

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

Voltage in low- and middle-income country (LMIC) contexts often falls outside the nominal range.[4] However, a lack of large-scale data has limited research on the broader economic impacts of

[4] Jacome et al. (2019) measure voltage quality for 25 households in Unguja, Tanzania, and find that customers

poor voltage quality. Most utilities and regulators have no way of measuring voltage as experienced by customers.[5] This problem is exacerbated in LMICs, where resource constraints prevent utilities from investing in improved technologies: the widespread deployment of smart meters, for example, can be prohibitively expensive (Dutta and Klugman, 2021).

2.1 Types of voltage quality issues

When voltage falls below the nominal range, appliances often cannot function properly. Lightbulbs will dim or flicker. Some appliances cannot be turned on, particularly if voltage falls to more than 20% below nominal. Some will experience failure of protective components, even as other components continue to function, burning appliances. Voltage spikes—extreme increases often lasting seconds or less—can also cause significant damages to plugged-in appliances. These are rare but sometimes occur as power returns after an outage. Over-voltage spells—modest but longer-lasting increases above the nominal voltage range—are less damaging than under-voltage spells as well as less common. We present data on these phenomena in Section 3.

How voltage fluctuations affect appliances is complex, non-linear, and not well understood. A single short but large voltage spike or sag can cause more damage than a more moderate but lengthier under- or over-voltage spell, but a simple average voltage metric will not capture this non-linearity. Fluctuations may also affect appliances differently than under- or over-voltage spells. Unlike reliability, where the System Average Interruption Duration Index (SAIDI) is a globally and industry-wide accepted indicator (NERC, 2020; Vugrin et al., 2017), existing indicators for voltage quality do not accurately capture the voltage issues common in low-resource settings, instead applying more to high-income settings with only minimal deviations from nominal (IEEE, 2018).

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

2.2 Causes of poor voltage quality

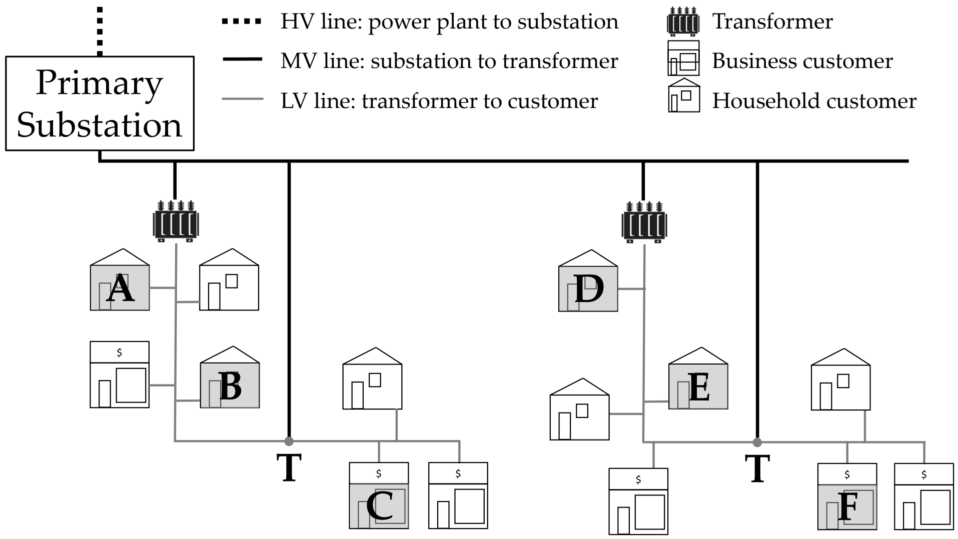
In most countries, high voltage (HV) cables transmit electricity from power stations to primary substations. Medium voltage (MV) cables then transmit this on to distribution transformers, and low voltage (LV) distribution lines then distribute power to residential and commercial customers. Figure 1 presents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

Transformer load and distance to transformer are key drivers of poor voltage quality. Transformer load is the aggregate electricity demanded by all customers connected to a transformer. As load increases, the transformer's output voltage drops, causing voltage to drop. Load variability

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.

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

Figure 1: Schematic of an electricity distribution network



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

therefore also increases customer voltage variability. If the transformer is overloaded—that is, when load exceeds transformer capacity—output voltage can drop below the target voltage range.

Distance to the nearest transformer worsens voltage due to impedance in LV lines and due to the increased load between the transformer and the customer (Jacome et al., 2019; Wolfram et al., 2023). The electricity grid intervention that we study (which we discuss in detail in Section 5) adds (or 'injects') new transformers to the grid, reducing the average load on existing transformers and also reducing the distance between customers and their nearest transformer.

Figure 1 visualizes these dynamics in an example grid. Customers A and D experience similar voltage because both are near the transformer, and their transformers have a similar load. E might experience worse voltage than D because they are farther from their transformer, but better voltage than B because there are fewer customers between E and the transformer than between B and the transformer. Adding two new transformers at T should improve electricity quality for C and F, and likely for B and E, by reducing the distance to their nearest transformer. It might also improve power for A and D by reducing the load on their nearest transformer.

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

3 Measuring voltage quality in Ghana

Ghana achieved high levels of electricity access earlier than most sub-Saharan African countries, with 64% of households connected in 2010 compared to the regional average of 33% (WB, 2010).

From 2012–2016, Ghana experienced a severe power crisis with periods of rolling blackouts in the face of power shortages. This crisis has been covered in the media (The Guardian, 2015; Al Jazeera, 2016; New York Times, 2016; BBC, 2016) and in academic research (Abeberese et al., 2019; Aidoo and Briggs, 2019; Briggs, 2021; Hardy and McCasland, 2019).[6] Access and reliability have improved significantly in Ghana in recent years, with household electricity access now 86% (SE4All, 2022; Kumi, 2020) and outage duration down to 30 minutes per day per our data. Less attention has been given to voltage quality, even though Google trends for searches of terms related to voltage quality and to outages in Ghana over the last 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 with customers residing across the Accra metropolitan region starting in 2018 (Figure A2 shows a picture of the device).[7] Each device is plugged in with either a household or business connected to the electricity grid.[8] This generates 337 million data points on voltage and outages as experienced by households and firms. To the best of our knowledge, this is the first large-scale collection of customer-level outage and voltage data in any low- or middle-income country.[9]

Ghana's nominal voltage is 230V. Appliances in Ghana are often rated for 220–240V, making them more vulnerable to moderate voltage fluctuations than appliances used in higher-income contexts which allow a larger input voltage range.[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 these targets. Panel A of Figure 2 displays data for 20 randomly selected devices during an arbitrarily chosen week. Several patterns are worth highlighting. First, there is significant heterogeneity in average voltage across customers, which may be due to differences in distance to the nearest transformer and in transformer load as discussed in 2.2 (see Figure A3 Panel A). Second, customers often experience fluctuations outside the recommended range. Third, voltage is consistently worst between 7–10pm, when load is highest.

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

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

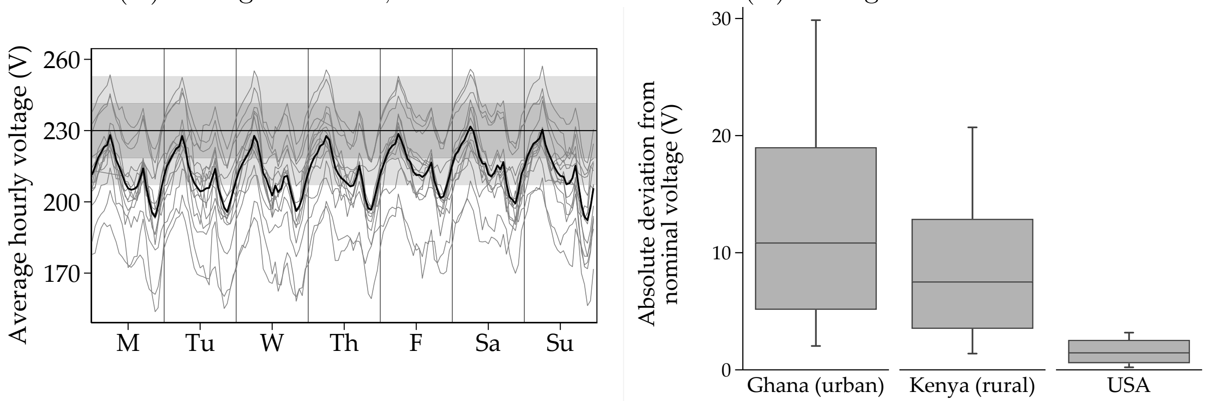
[8] Each participant receives financial compensation for each month they keep the device plugged in. Section 5 presents more information on site and respondent selection.

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

[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

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



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

Fourth, nearly all deviations outside the nominal range constitute voltage drops.

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

Table 1 presents statistics for several voltage quality indicators designed to give a comprehensive picture of customer-level voltage quality, over the period from march 2019-November 2020 (before local grid improvements). Panel A indicates that average voltage was 219V, outside the voltage rating range for most appliances in Ghana (220–240V). In a given hour, voltage was on average 10-20% below nominal 17% of the time and more than 20% below nominal 5% of the time. During peak load periods, the fraction of time more than 10% below nominal exceeds 30%. Voltage quality issues are significantly more common than power outages, which occur 2.5% of the time (18 hours per month).

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

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

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

(B) Monthly data

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

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

4 Self-reported economic costs of poor voltage quality

Voltage quality can affect economic productivity and well-being in four main ways. First, poor voltage can restrict the productive use and utility of electric appliances. Second, it can damage appliances and require spending on repairs or replacements. Third, it can require investments in devices designed to protect against voltage fluctuations (such as voltage stabilizers) or in backup energy sources. Finally, these mechanisms may further lower long-term investment by lowering the expected value of appliances.

We survey 2,001 electricity grid customers—997 households and 1,004 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. 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%). Per data from the Ghana Statistical Survey, sample respondents are largely representative of households and businesses in the Accra Metropolitan Area (Table B2). Businesses in the survey sample are primarily micro-enterprises

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

Table 2: Baseline household and business electricity quality issues

	Mean	SD	Min	25^{th}	50^{th}	75^{th}	Max	N
Panel (A) Experience with outages and voltage								
Reported number of outages in past month	6.86	5.50	0	4	6	8	90	2001
Reported total outage hours in past month	39.15	47.71	0	12	24	48	300	2001
Reported hours of bad voltage in past month	47.72	100.34	0	0	15	60	720	1988
Panel (B) Economic impacts								
Any appliance damaged by voltage in past year	0.26	0.44	0	0	0	1	1	2001
Amt spent on burnt/broken apps in past year	44.85	140.19	0	0	12	43	2586	511
Any voltage protective device	0.25	0.43	0	0	0	0	1	2001
Value of voltage protective devices	60.31	119.55	3	16	26	57	1397	261
Uses an alternative energy source	0.05	0.21	0	0	0	0	1	2001
Outages are obstacle to business	0.92	0.28	0	1	1	1	1	975
Voltage fluctuations are obstacle to business	0.31	0.46	0	0	0	1	1	975
Panel (C) WTP for improved service quality								
Max monthly WTP for perfect reliability	3.52	5.42	0	0	2	5	78	2001
Max monthly WTP for half of curr. outages	1.67	3.40	0	0	0	2	60	1964
Max monthly WTP for half of curr. volt. fluc.	1.95	4.43	0	0	0	2	52	512
Share of govt. investment to reducing outages	0.17	0.12	0	0	0	0	1	1061
Share of govt. investment to improving voltage	0.15	0.13	0	0	0	0	1	1061

Values are in USD. Spending on burnt appliances is among those reporting any voltage-related damage. Value of voltage protective devices are among those with any such devices. Voltage protective devices include general purpose voltage stabilizers and more specialized devices such as fridge guards and TV guards. Alternative energy sources include generators, solar panels, and wet cell batteries. Only a subset of respondents in the baseline survey were asked their WTP for reduced voltage fluctuations. Data on share of government investment comes from the endline survey - this was not asked about in the baseline survey.

with one or two employees including the owner or manager, and consequently employees, revenues, and profits are somewhat lower than the Accra median.

4.1 Customer self-reports of power quality and reliability issues

Customers behavioral responses are driven by their perceptions of power quality, which could differ from the technical measures discussed in Subsection 4.4. In this section, we explore how perceptions of power quality and reliability are related to measured power supply and political beliefs.

Table 2 reports summary statistics for households' and businesses' experiences with electricity issues in March 2021. Respondents reported 39 hours of power outages and 48 hours with bad voltage over the past month on average.

Self-reported outages correlate strongly with GridWatch-measured outages (Figure A4), but respondents still under-report actual outages by more than half. There is a much weaker correlation for voltage, with customers under-estimating the frequency of low quality voltage by an order of magnitude. Individuals may only be able to detect voltage problems when voltage drops farther below the threshold of 10% below nominal voltage we use to define low voltage with the GridWatch data. They may also not observe voltage issues during periods they are not actively using appliances

Table 3: Political affiliation and power quality perceptions

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

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

that are sensitive to voltage.[12] This may also be driven by measurement error in voltage quality, which varies across customers within a site much more than power outages.

4.2 Political bias in electricity quality recall

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

To examine this, we ask respondents two questions about the government's performance on electricity issues, and then ask enumerators to (privately) assess the respondent's political preference. This yields a binary indicator of whether the respondent appears to support the current government or not. We examine whether this is correlated with self-reports of power quality, controlling for power quality and including a site fixed to control for geographic heterogeneity in income.

Table 3 presents the results. Respondents who support the government report fewer outages and fewer hours of bad voltage. In theory, this could reflect a causal effect of power quality on political support: respondents may attribute good power quality to government efficacy, and this may increase government support. However, we see no correlation between government support and power quality as measured by the GridWatch devices (Table B3). Instead, respondents may consume information provided by media representatives or politicians aligned with their political preferences, and these actors share biased information. This underscores the importance of objective data to complement self-reported data.

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

4.3 Costs and relative value of reliability and voltage quality improvements

Panel B of Table 2 shows that poor power quality has economic costs. 26% of respondents report experiencing damages to appliances due to voltage issues in the past year. These respondents spent $45 on repairs or replacements (around 3 months of average electricity spending, or around 15% of monthly household income and business revenue). To protect against these damages, customers often purchase equipment that protects appliances from bad voltage: 25% of respondents have at least one voltage protective device, with an average estimated value of $60.[13] 92% (31%) of businesses report that outages (voltage fluctuations) are an obstacle to business operations. Just 5% of respondents have an alternative energy source (generators, solar panels, or wet cell battery): most have no alternative when grid electricity service is poor.

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

First, we use a standard set of stated preference questions to measure willingness to pay (WTP) for improvements in the reliability and quality of their electricity connection. We use a binary search to determine the maximum increase in monthly electricity costs the respondent is willing to pay for an improved connection (beyond what they currently spend), first asking about a randomly chosen price and then iteratively asking about either higher or lower prices based on the prior response.[14] Panel C of Table 2 shows that respondents are willing to pay on average an additional $3.5 per month (an 18% increase in electricity spending) for access to an electricity connection with no voltage fluctuations or outages (it is worth noting that this includes around 30% of respondents who had a WTP of $0). WTP for a connection with no voltage fluctuations and half the respondent's baseline monthly outages and WTP for a connection with no outages and half the baseline level of voltage fluctuations are similar—$1.7 and $2 per month, respectively, representing around 10% of monthly electricity spending (Figure A5 presents the full distributions).

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

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

[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%).

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

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

4.4 Correlates of customer-level power quality and reliability

Poor voltage quality cuts across wealth and income: monthly hours with low voltage do not vary significantly by wealth, income, or revenue (Table B1). The only respondent characteristic correlated with voltage quality is distance to the nearest transformer: being 100 meters farther away is associated with 33 more hours (19%) of low voltage per month (Figure A3 shows this relationship graphically). This aligns with the causes of poor voltage quality discussed in Subsection 2.2. Higher voltage quality is correlated with lower WTP for improved electricity connections, lower probability of appliance damage, and lower value of protective devices owned (Table C11).

On the other hand, a one standard deviation increase in the wealth index (proxied by structure quality, appliance ownership, and education) is associated with a 0.6 hour reduction in outages per month (4%). This could reflect either customer sorting on attributes, utility investment in higher-revenue areas, or a causal effect of reliability on wealth. In theory, the correlation between reliability and wealth may be due to ownership of generators by higher-wealth businesses and households. However, only 4% of respondents have a generator—this is therefore unlikely to explain much of the correlation. In addition, if this were the channel, we might also see a correlation between wealth and voltage quality, but we do not. The lack of a similar relationship for voltage may also indicate that voltage quality is difficult to observe for potential residents, or utilities may not be able to target voltage improvements in the way they do outages.

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). \$13.9 million was spent on low-voltage (LV) line bifurcation in the Achimota, Dansoman, and Kaneshie districts of Accra, Ghana.[15] We estimate the effects of this investment on power quality and economic outcomes using a difference-in-differences strategy.

5.1 Low-voltage line bifurcation

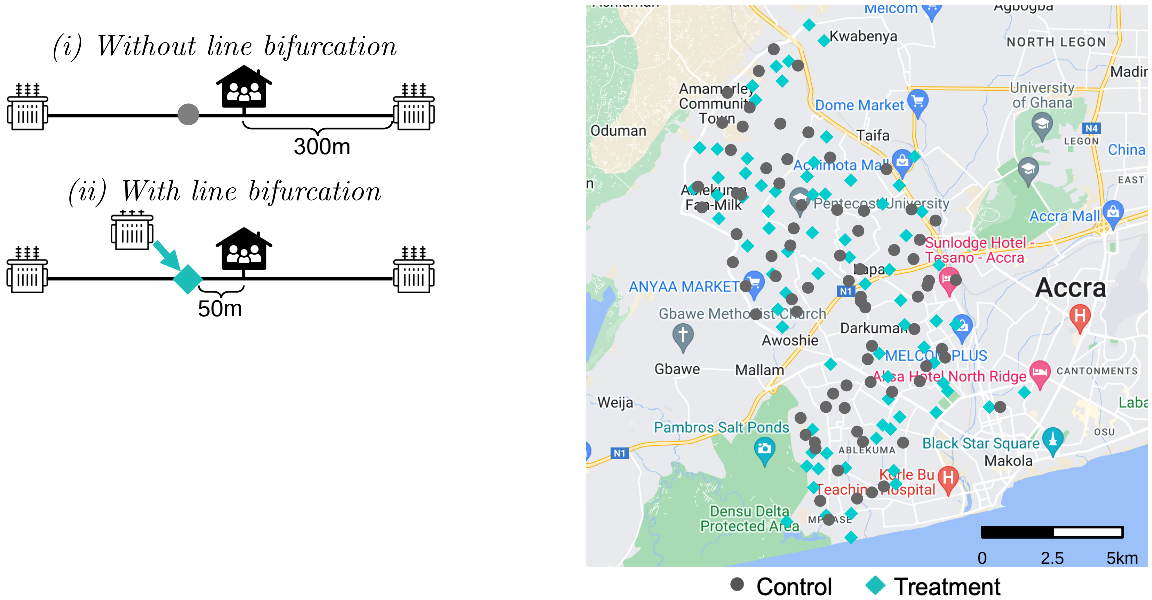
Line bifurcation involves adding a new transformer to the LV network with the goal of reducing average transformer loads as well as "to reduce the length of the low voltage circuits to ensure they do not exceed a length that affects the quality of service and a technical loss threshold" (MCC, 2014). Panel A of Figure 3 provides an illustration. As discussed in Subsection 2.2, the reduction in distance and in transformer load should increase average voltage, in particular for customers whose distance to the nearest transformer decreases the most.[16]

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

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

Figure 3: Line bifurcation control and treatment sites across Accra

Panel (A) Panel (B)



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

An MCC contractor selected the new transformer locations, targeting segments on the grid that were approximately 200 to 300 meters from the nearest existing transformer. Other than this distance criterion, the contractor had very limited local data to inform location decisions. They did not have access to any type of socioeconomic or demographic characteristics, or utility data on things like the number of metered connections, bill payment rates, or electricity demand (sub-district electricity data in general is largely unavailable—the utility only prepares district-wide data). The one exception to this is that the contractor obtained analog readings of transformer-level load measuring the highest instantaneous load experienced at a transformer since the last reading. However, these must be reset manually and are not reset at a fixed schedule, and are therefore a crude and noisy measure of load. 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'). Using spatial data covering the entire electricity network in Accra, our research team identified segments of the LV grid that were between 200 and 300 meters from both any existing transformers and any treatment locations—thus following the main criterion for treatment site selection—and then randomly selected 75 locations from this set ('control sites'). The distribution of distances to the nearest existing transformer is similar for treatment and control sites (Panel A of Figure A6). The 76 treatment sites and 75 control sites, shown in the map in Panel B of Figure 3, comprise the 151 sites of our study sample.

We then use maps of the distribution network to define the boundaries for data collection in each site (Figure A7 presents an example). We first identify segments of LV lines that are <200 meters from the new or placebo transformer location but >300 meters from any existing transformers. Customers within 25 meters of these LV segments are those whose electricity service would likely be affected by a transformer injection. Defining these boundaries also reduces the likelihood of spillover voltage improvements in control sites from nearby transformer injections (we find no evidence that control sites located closer to treatment sites experienced greater power quality improvements than those located farther from a treatment site; see Table B4).

5.2 Data

We began collecting voltage quality and reliability data at all 151 sites by March 2019 (see Klugman et al. (2019) for more detail on the deployment methodology). We focus on data collected between March 2019 and April 2023, encompassing the transformer construction period which lasted from October 2020 to March 2021 (Figure A8 presents a timeline).

Baseline surveys with 6-7 businesses and 6-7 households in each site were conducted in March–April 2021 and endline surveys in July–September 2022.[17] There is no overlap between business and household survey respondents and respondents that received a GridWatch device.[18]

To lend support to the quasi-random nature of the assignment mechanism, we conduct a battery of tests examining baseline differences between control and treatment sites. Levels and pre-trends in outages and voltage by site treatment status are statistically indistinguishable before the line bifurcation intervention (see Panel A of Figure 4 and Panels A and B of Figure A9). Levels and trends in nighttime radiance data from VIIRS are also nearly identical prior to the intervention (Figure A10). Respondents' socio-economic characteristics at baseline are balanced across treatment and control sites (Table B2).[19] The distributions of distance between each survey respondent and the nearest existing transformer prior to line bifurcation are statistically indistinguishable across control and treatment sites (Panel A of Figure A6).[20] This evidence of baseline balance and parallel pre-trends, in conjunction with the quasi-random institutional design of the line bifurcation investments, support the logic that a difference-in-differences design will identify the causal impacts of these electricity grid improvements.

Of 2,001 respondents surveyed at baseline, 1,575 were surveyed at the endline one year later. Attrited respondents are similar to non-attrited respondents along most socioeconomic characteristics, though they differ along a small number of variables commonly associated with attrition

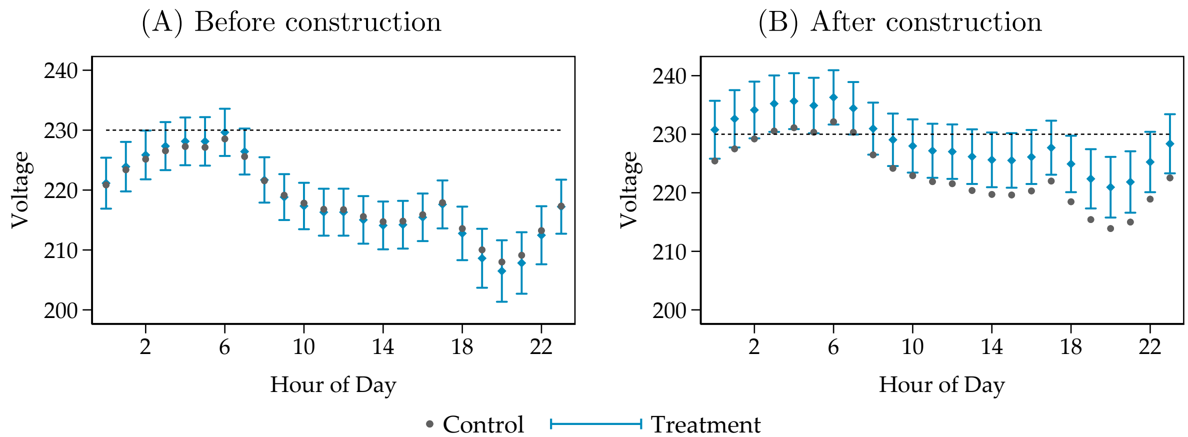
[17]Due to COVID-19-related delays, baseline surveys were conducted while line bifurcation construction activities were being completed. However, voltage quality did not improve significantly until April 2021 (Figure A9). In addition, the short period between construction and baseline surveys is likely to have been too short for households or businesses to notice any sustained improvement, let alone act on this improvement and have it reflected in socioeconomic outcomes—most of which are measured over the month or year prior to the survey date. In support of this, we find no baseline differences in respondent outcomes by treatment status (Table B5).

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

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

[20]Prior to construction, respondents at control (treatment) sites are on average 233 (253) meters from the nearest transformer (see Figure A6 for the full distribution).

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



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

such as age, household size, and rental status (Table C1). There are no socioeconomic differences between attrited respondents in treatment and control locations (Table C2).

To verify compliance with planned transformer injections, we use construction progress reports submitted by the private contractor, tracking each site. In addition, we conducted site visits between November 2020 and October 2021 to confirm the presence (absence) of new transformers at treatment (control) sites. Subsection 5.6 presents robustness by construction completion.

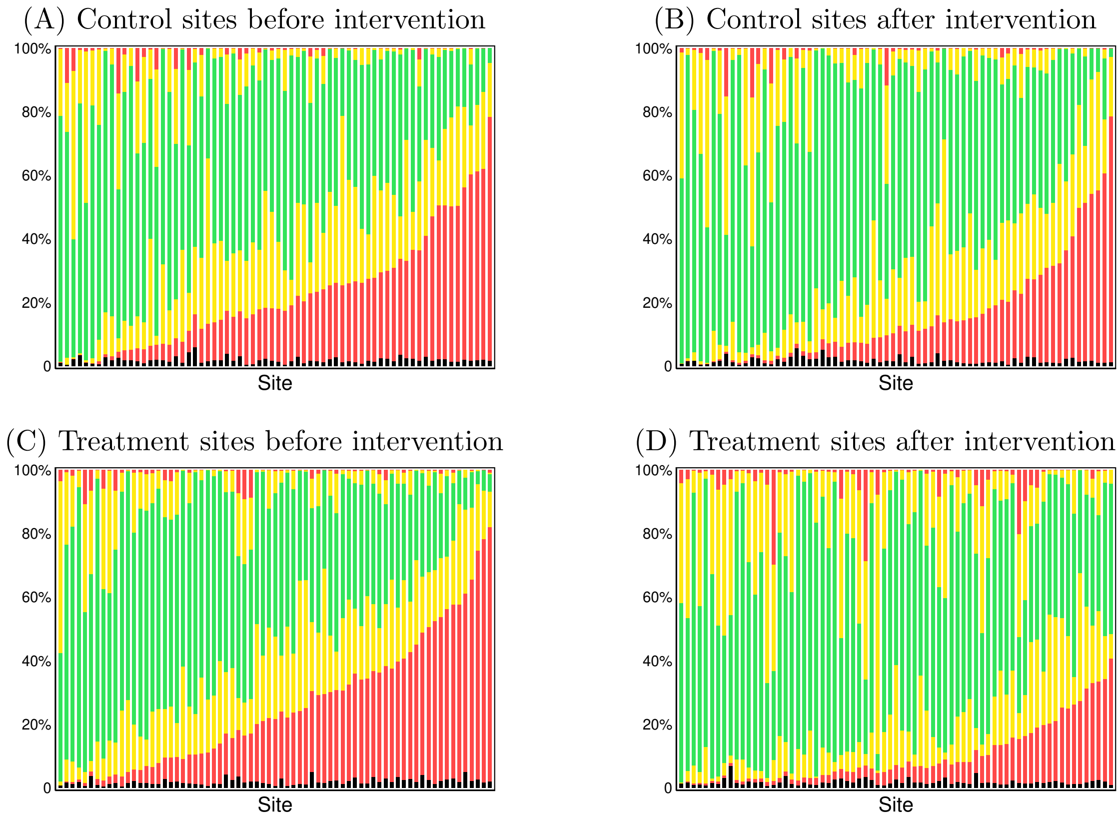
5.3 Results: Impact of line bifurcation on power quality

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

Figure 5 illustrates the distribution of effects across sites. Green areas indicate the fraction of time electricity fell within ±5% of nominal voltage. Yellow areas below (above) the green areas indicate deviations of between 5–10% below (above) nominal voltage. Red areas below (above) the yellow areas indicate deviations of at least 10% below (above) nominal voltage. Black areas indicate outages. The graphs show the distribution separately for each site, ordered by time spent with power more than 10% below nominal voltage.

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

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.

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

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

Y_{it} is an outcome experienced by device i at time t. $\boldsymbol{\Gamma_s}$ are site fixed effects, which subsume a 'Treat' dummy. $\boldsymbol{\Gamma_t}$ are time fixed effects that vary across regressions. β_1 and β_2 capture changes in overall voltage quality or outages after and during construction relative to the pre-construction period. β_3 captures the treatment effect of interest.[21] Standard errors are clustered by site in all regressions.

Table 4 presents the results. Columns (1) and (2) use hourly data to estimate the impact of line bifurcation on minutes of power outages and on average voltage.[22] The transformer injection intervention increased average voltage by 5.5V relative to control sites, but had no impact on power outages. Columns (3) and (4) use monthly data to estimate the impact on low-voltage spells

[21] Event study results showing impacts by quarter are shown in Panels C and D of Figure A9.

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

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

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

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

(periods during which voltage drops at least 10% or 20% below the nominal level).[23] The treatment caused a 37 (28) hour decrease in the monthly hours of spells with voltage more than 10% (20%) below nominal, respectively—a 51% decrease.

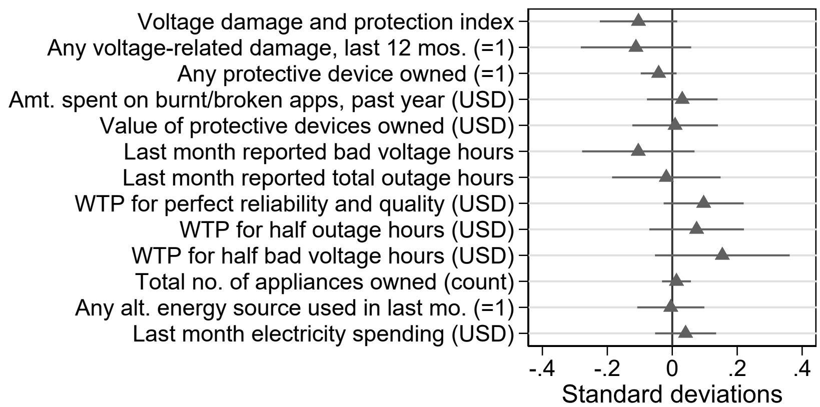
We also see a significant reduction in the *severity* of low-voltage spells in treatment sites post-construction relative to control sites: the longest spell in a month is 4.5 hours shorter and mean voltage during low-voltage spells is 14V higher.[24] These results show that line bifurcation caused voltage improvements at both the extensive and the intensive margin. Voltage gains in treatment sites relative to control sites were stable for a year after construction completion, but decreased slightly and were no longer significant after around 18 months (Panel C of Figure A9).

It is worth noting that Figure 4, Table 4, and Figure 5 also show voltage quality improvements over the study period at control sites (the causal voltage improvement at treatment sites is on top of this improvement at control sites). These improvements do not appear to be due to spatial spillovers from nearby treatment sites as the voltage improvement at control sites does not differ significantly by distance to the nearest treatment site (Table B4). Furthermore, line bifurcation did

[23] 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.

[24] Table C5 and Table C6 provide additional estimates. Treatment decreases the likelihood that voltage falls more than 20% below nominal voltage in a given hour by 4 percentage points (50%); 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.

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



Coefficients and 95% confidence intervals from Equation 2, pooling business and household respondents. Standard deviations relative to the baseline control mean. The voltage damage and protection index composes 'any voltage-related damage' and 'any protective device owned'. Table B5 shows non-normalized outcomes.

not significantly change distances to the nearest transformer in control sites (Panel B of Figure A6), and combining changes in control site device distances to the five nearest transformers at endline with how those distances correlate with average voltage suggests this would only explain a small share of the control site increase in voltage post-construction.

Broad-scale voltage improvements may be attributable to other large-scale MCC investments in the grid at the time under the Ghana Power Compact (such as the construction of additional primary substations and bulk supply points; MCC, 2014), to changes in electricity consumption due to COVID-19, or to other economic forces.

5.4 Results: Impact on customer electricity experiences

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

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

For outcome Y_{it} experienced by respondent i at time $t \in \{0, 1\}$. β_3 captures the differential outcome being observed post-construction in treatment sites—the treatment effect of interest. $\boldsymbol{X_i}$ are baseline socioeconomic controls.[26] Standard errors are clustered by site in all regressions.

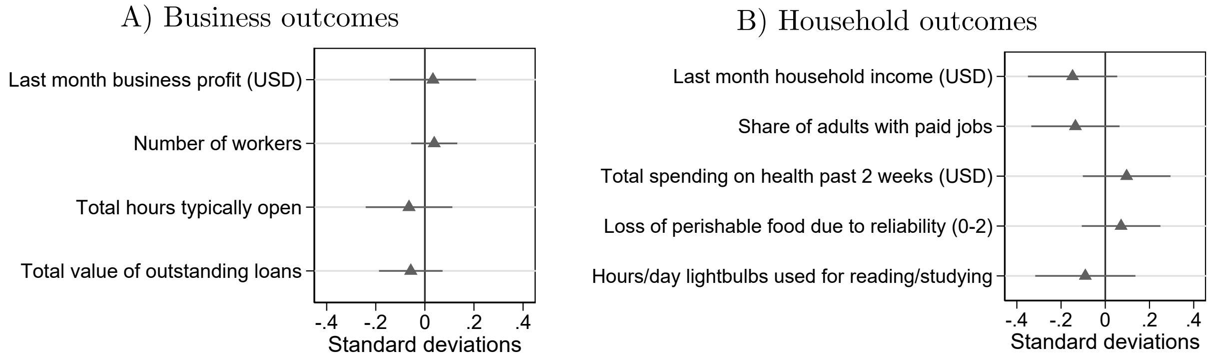
Figure 6 presents the results, normalized around the baseline control mean, pooled for businesses and households.[27] We estimate a 0.1 SD reduction (p=0.09) in a voltage damage and protection index comprised of two components—whether appliances were damaged by voltage in the past

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

[26]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.

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

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



Coefficients and 95% confidence intervals from Equation 2. Standard deviations relative to the baseline control mean. Table B6, and Table B7 show non-normalized outcomes for Panels A and B, respectively.

year and whether the respondent has any voltage protective device—implying a 20% decrease in voltage-related damages.

We see no impacts on any other electricity-related outcomes. This may have been because the broader voltage quality and quality improvements across Accra improved voltage quality at control sites sufficiently to address most related concerns. Improvements in reported electricity outcomes across the whole sample may also have been due to seasonal differences in energy use and economic activity due to the differences in the timing of the two surveys.[28]

The broad electricity improvements are reflected in estimated average differences between baseline and endline electricity outcomes. The probability of having had an appliance damaged by voltage issues over the past 12 months, ownership of voltage protective devices, and WTP for improved electricity connections all fall across all sites after construction, and self-reported daily hours of bad voltage was nearly zero during the endline even at control sites (Table B5). Seventy-one percent of respondents at endline say voltage is much better than two years ago (19% say it is slightly better), and businesses are 19 percentage points less likely to say bad voltage is an obstacle to business operations at endline compared to baseline. Respondents report improvements in electricity quality and significant decreases in voltage damages, costs, and protective device ownership after the construction period. WTP for improved electricity connections also falls on average in the post period. Use of alternative energy sources such as generators and solar panels was low at baseline and did not change over time.

5.5 Results: Impact on socioeconomic outcomes

Panels A and B of Figure 7 show no treatment impacts on business and household outcomes, respectively (Table B6 and Table B7 present these and additional outcomes).

What can explain this? There are several plausible hypotheses. It may simply be that voltage is less important to economic activity, or that the impacts of average voltage improvements are non-linear, with larger marginal effects for increases at lower levels of voltage. The investment may

[28]Voltage is typically better in July-September, which coincides with the endline survey (Panel A of Figure A9).

not have caused a sufficiently large increase in power quality, or the voltage improvements at control sites may have been enough to address the most severe voltage issues. Alternatively, chronically low-quality and unreliable electricity may cause customers to have a limited stock of electric appliances, and treatment effects may only be realized in the longer term, as customers improve or expand their stock of appliances. We observe no difference in appliance acquisition after construction by treatment status: 37% of respondents at endline in both treatment and control sites reported acquiring at least one new appliance since the baseline survey, with no difference between businesses and households (Figure A11). However, 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 Heterogeneity and robustness checks

We find no statistical differences in the impact of line bifurcation on socioeconomic outcomes by baseline voltage quality, defined as being above or below the median daily hours of voltage within 10% of nominal average (Column 1 of Table B8), despite the fact that treatment sites with below-median baseline voltage experienced greater voltage improvements (Table B9). This suggests that the lack of impacts is not driven by respondents whose power quality was already within an acceptable range at baseline. We also evaluate heterogeneity by baseline characteristics that reflect the importance of voltage quality for respondents, including reported electricity importance (for businesses), willingness to pay for perfect electricity reliability and quality, and ownership of protective devices. Again, we find no significant differences (Columns 2–4 of Table B8).

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

5.7 Cost–benefit analysis

MCC spent \$13.9 million on low voltage line bifurcation in the Achimota, Dansoman, and Kaneshie districts of Accra, Ghana, which have an estimated combined population of around 49,000 households (GSS, 2014), or \$286 per household.

To estimate the cost-benefit ratio, we first use stated willingness to pay (described in Subsection 4.3) as an estimate of value. For an investment that generates perfect voltage quality but does not reduce outages (similar to what we find), an upper bound for the value to consumers is

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

respondent WTP for a connection with perfect voltage quality and half their current outages.[30] Customers report being willing to pay an additional \$1.67 per month for such an improvement, or \$20 per year. Assuming a new transformer generates 30 years of usage, and using an annual discount factor of $\delta = 0.9$, this yields aggregate benefits of \$191 per household, or \$9.3 million across the 49,000 households in the three districts. This back of the envelope calculation could be an underestimate (if respondents are credit constrained) or an overestimate (the investments did not generate perfect voltage quality or reduce outages) but likely approximates the benefits. Even so, it falls slightly below the costs of the line bifurcation investment.

Alternatively, we can calculate the benefit in terms of avoided investment in voltage protective devices (\$15.08) and annual repairs and replacements of broken appliances (\$11.66). Eliminating all protective devices and 100% of damage repair/replacement expenditures every year for 30 years (discounting at $\delta = 0.9$) for all 49,000 households yields benefits of \$12.4 million, still falling short of the investment cost.

These analyses consider only the benefits accrued to electricity customers (that is, households and businesses). Grid investments may generate benefits for the utility by reducing technical losses or avoiding the long-term damage to transformers incurred when a transformer operates at excessively high load (and thus reduce the utility's maintenance and replacement costs). Improved capacity might also help support demand growth and new loads due to reduced load per transformer, increasing utility revenues. We do not consider these utility-specific benefits in the cost-benefit analysis but conjecture that those savings would have to be quite large to justify the costs of the line bifurcation program.

6 Conclusion

Global energy policy in low- and middle-income countries has thus far placed limited focus on the role of voltage quality for economic activity, in part due to data limitations for measuring both the severity of voltage problems and the impact on households and businesses. We analyze 337 million temporally and spatially high-frequency power quality measurements, as well as 2,000 household and business surveys, to generate some of the first evidence on the large-scale economic impacts of voltage quality problems.

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

An intervention that added transformers to the grid increased average voltage by 5V—especially reducing the most severe voltage problem—and modestly reduced voltage-related damages and

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

ownership of protective devices. However, the investment had no impact on household and business outcomes such as electricity spending, appliance ownership, business profits, and household income. The economic benefits of voltage improvements may be larger at lower baseline voltage levels, or take longer than a year to materialize. Still, governments may prefer to invest in other publicly provided goods, or to identify more cost-effective ways to improve voltage quality.

These results present novel evidence on the economic costs of voltage quality, while at the same time highlighting the difficulty of achieving meaningful voltage improvements through infrastructure construction. We offer a framework with which to evaluate voltage quality investments. Resource-constrained governments will need to evaluate the economic benefits of voltage improvements against the high cost of these infrastructure investments.

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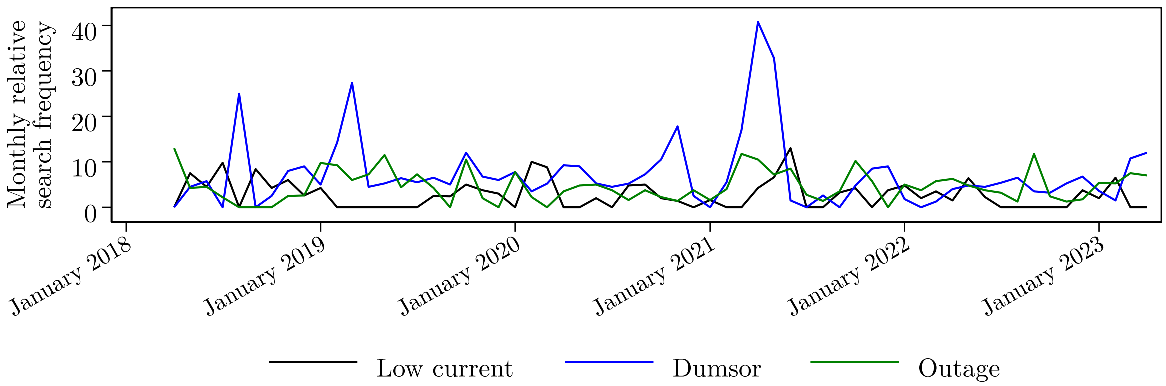
A Appendix Figures

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



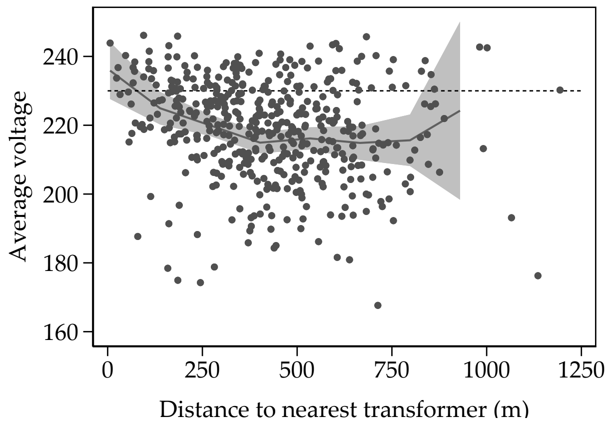
Data are aggregated from weekly Google Trends data for the specified search terms. Relative search frequency is calibrated to the maximum search interest across the three terms over the time period. "Low current" is the most common phrase used in Ghana to refer to issues related to voltage. "Dumsor",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

Figure A2: A GridWatch device

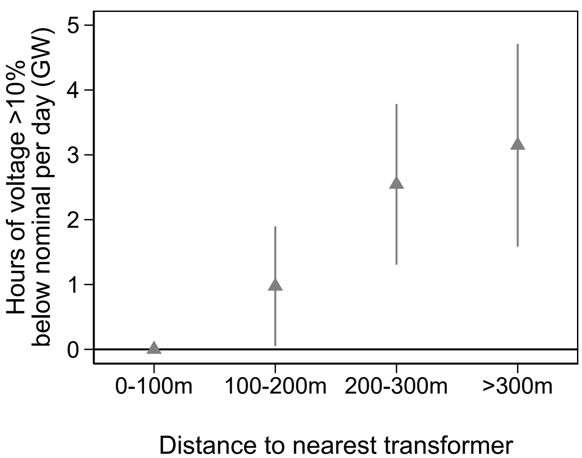
A GridWatch device, part of nLine's GridWatch technologies used to measure power outages and voltage. Each GridWatch device measures voltage in real-time, stores this on a local SD card, and sends the data to the cloud via a sim card whenever local cellular service permits. A back-end computing technology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

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

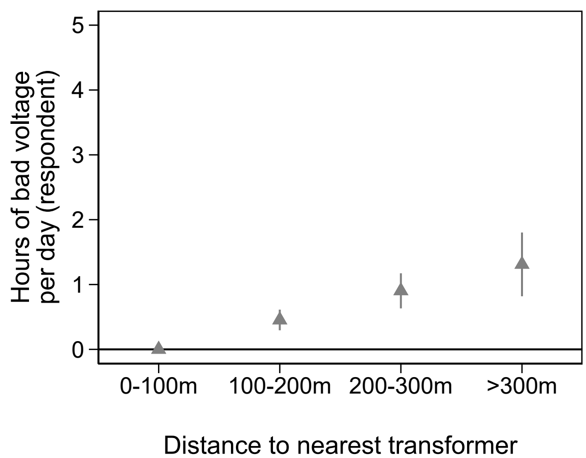
Panel (A) Raw correlation with GridWatch devices



Panel (B) GridWatch devices

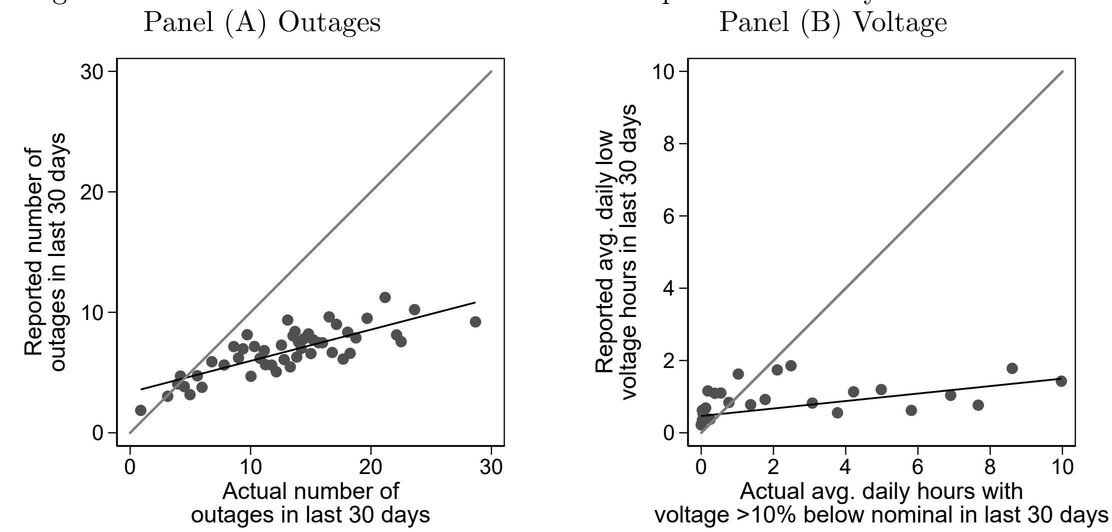


Panel (C) Self-reported



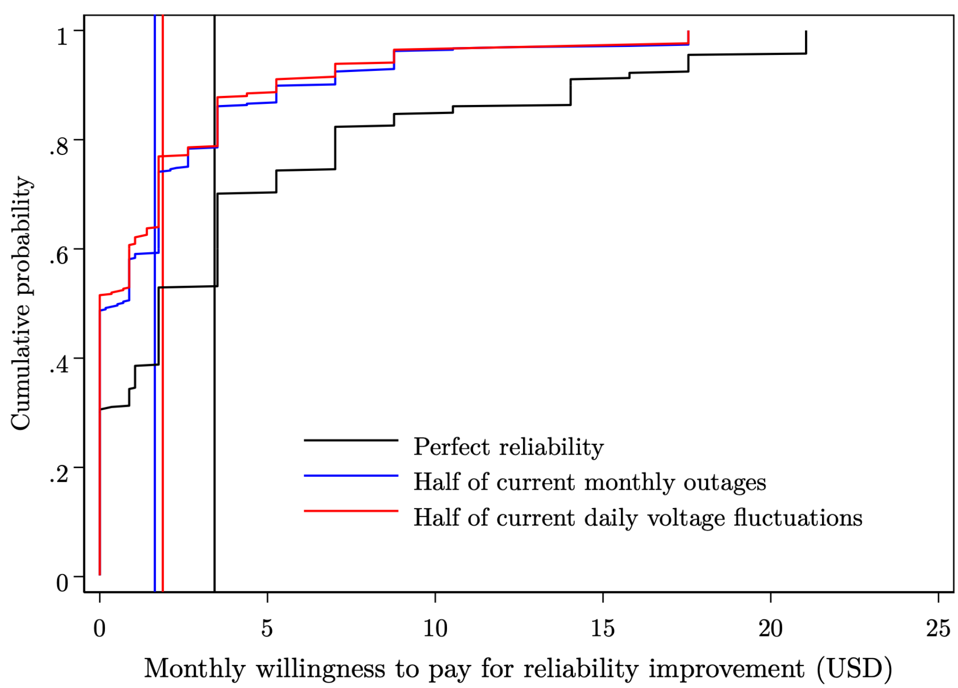
Panel A shows device-level average voltage by the distance along the electricity network from that device to the nearest transformer using GridWatch data from Ghana (described in Section 3). The black line shows the best fit from a local polynomial, and the shading show a 95% confidence band. For Panel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

Figure A4: Correlations between measured and reported electricity characteristics



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

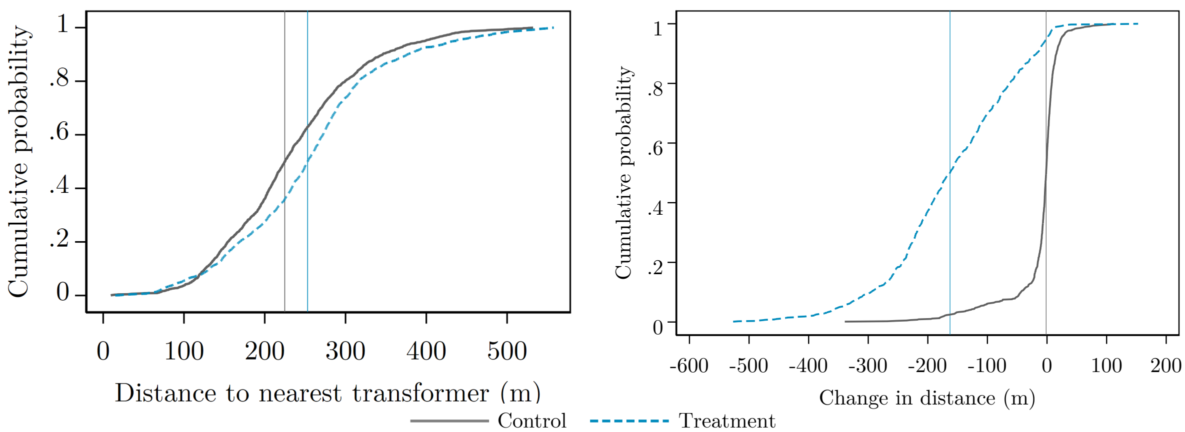
Figure A5: Willingness to pay for electricity connections with particular characteristics



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

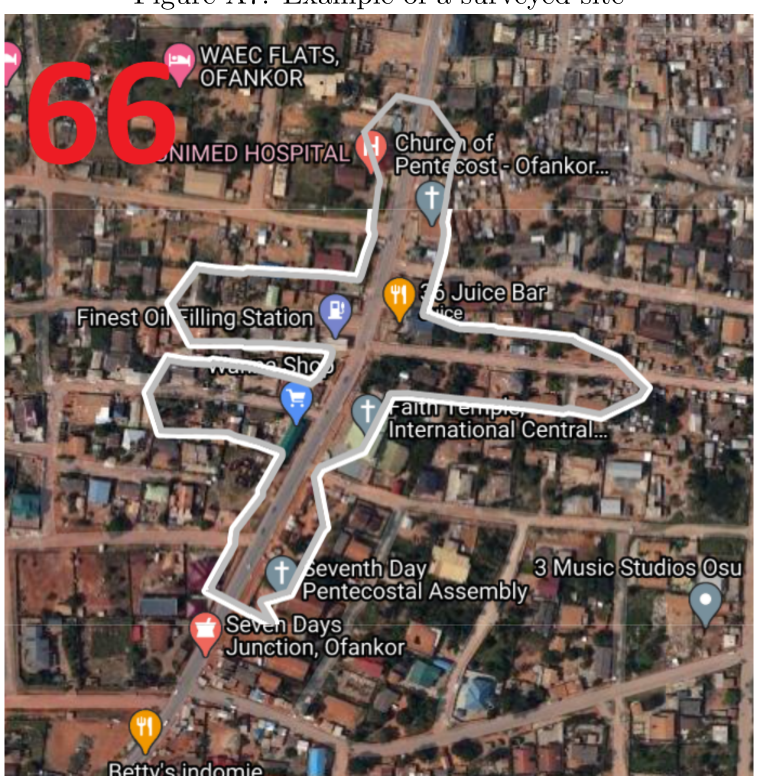
Figure A6: Distance between each respondent and their nearest transformer

(A) Before construction (B) Change from before to after construction



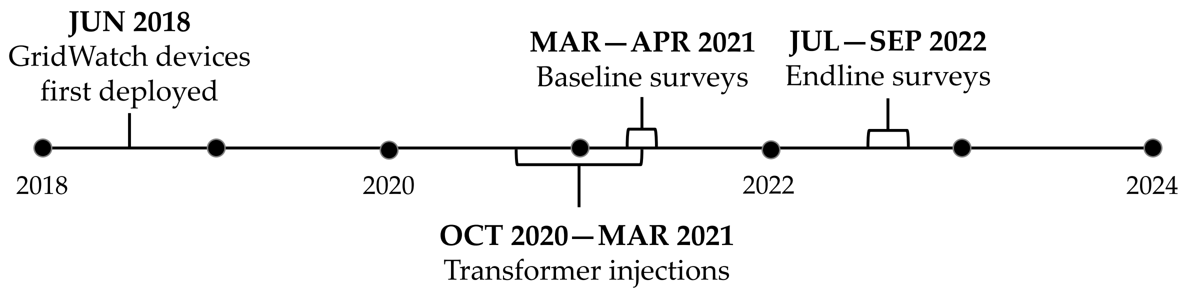
Panel A shows the distance (in meters) from each respondent to the nearest transformer at baseline to endline for survey respondents. Panel B shows the change in this distance from baseline to endline. The figures includes a small number of individuals who moved within the survey sites between baseline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

Figure A7: Example of a surveyed site



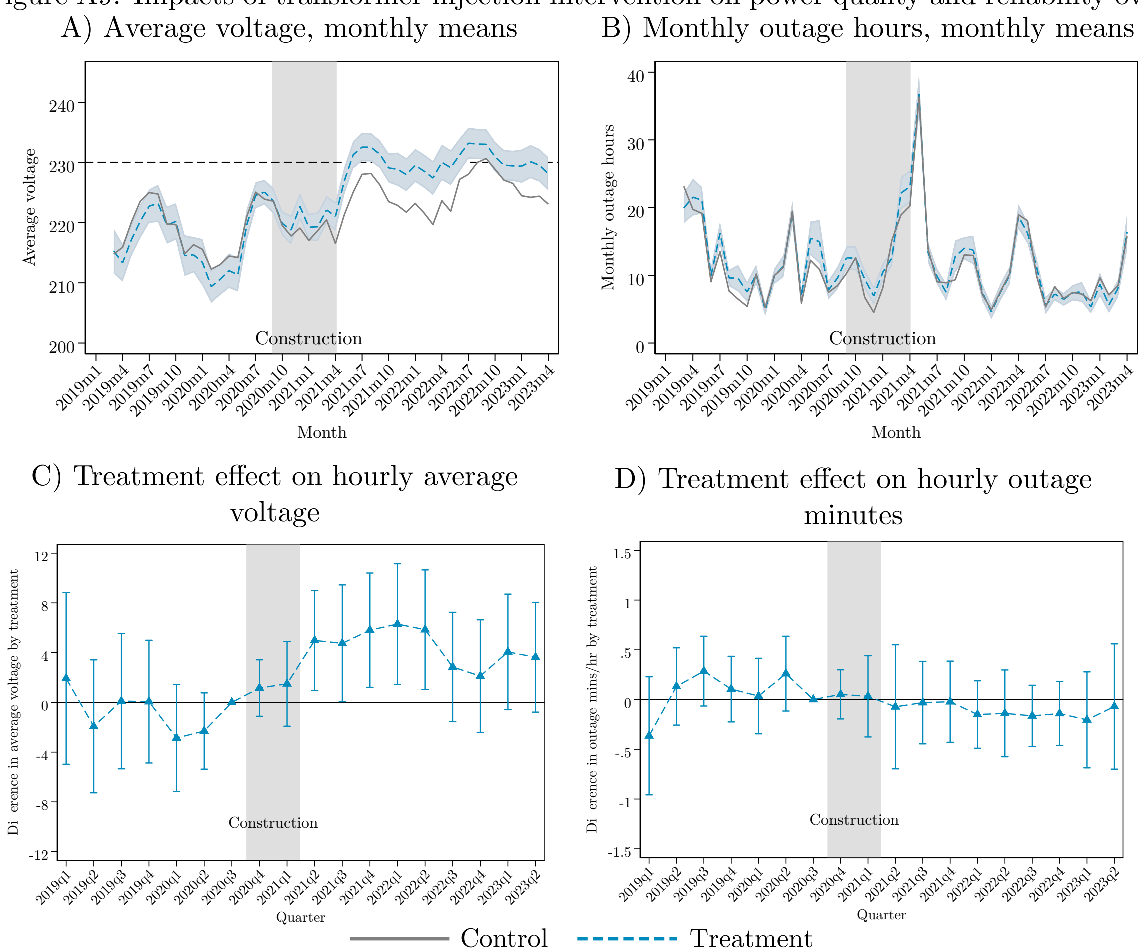
A sample site map where field officers conducted surveying. The outline in gray denotes the area within 200 meters of the proposed injection site and at least 300 meters from an existing transformer along the electricity network.

Figure A8: Project timeline



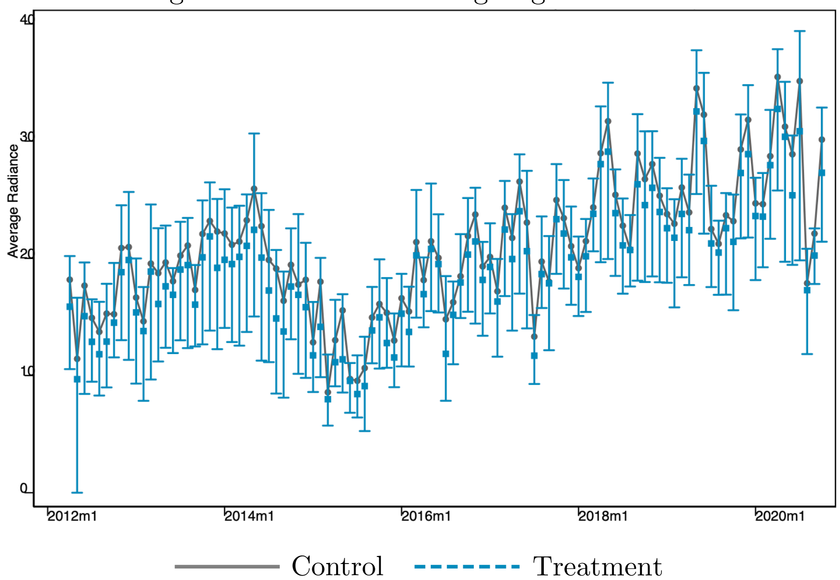
Timeline of research and construction activities. GridWatch data were collected continuously in the months after device deployment. The analyses in this paper include GridWatch data collected through April 2023.

Figure A9: Impacts of transformer injection intervention on power quality and reliability over time



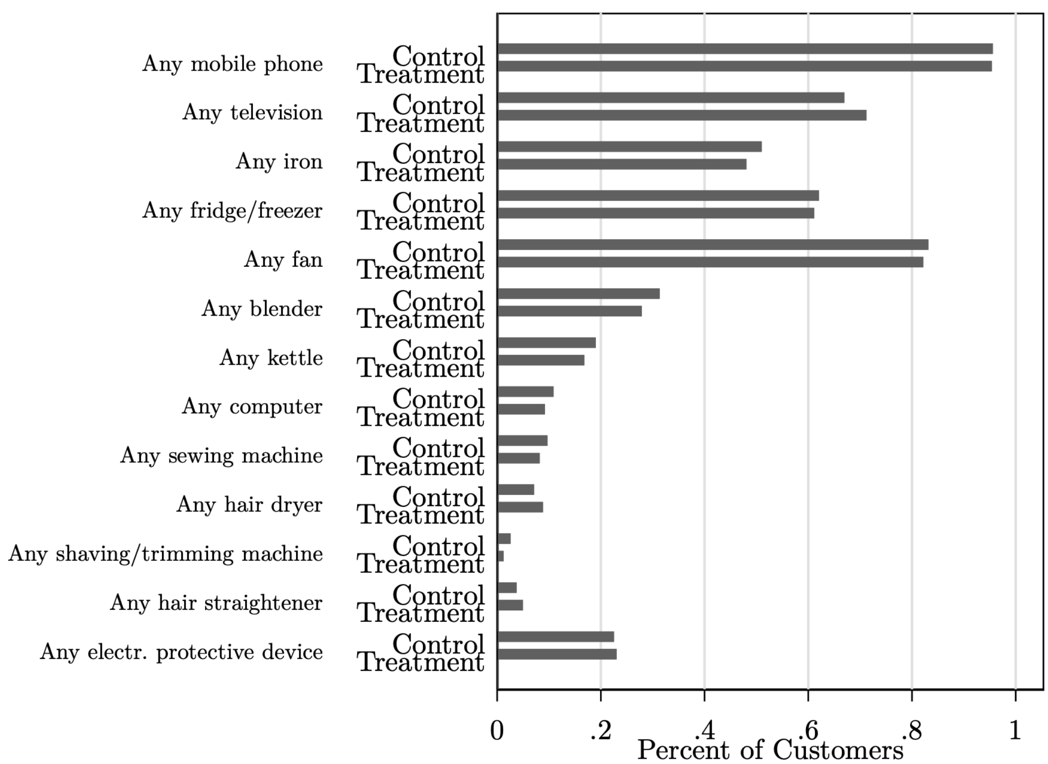
Panels A and B show monthly mean values by treatment. with 95% confidence intervals. Panels C and D show estimated coefficients and 95% confidence intervals from a regression of outcomes on site treatment status by quarter, controlling for hour of day, week of year, and site fixed effects. SEs clustered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

Figure 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.

B Appendix Tables

Table B1: Baseline correlates of power quality and reliability

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

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

Table B2: Baseline balance by site status

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

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

Table B3: Does power quality affect political preferences?

	(1)	(2)	(3)
Hours bad voltage per day	0.000	-0.000	0.002
	(0.002)	(0.003)	(0.004)
Hours outage per day	0.014	0.037	0.011
	(0.031)	(0.035)	(0.115)
Observations	1565	1565	1561
Mean	0.340	0.340	0.340
Week FE		Yes	Yes
Site FE			Yes

Outcome variable is a dummy for whether the respondent supports the government (34% do). 66% of respondents either support the opposition or are neutral. A 1 SD increase in 'hours outage per day' would correspond to 0.5 additional hours. A 1 SD increase in 'hours bad voltage per day' would correspond to 6 additional hours.

Table B4: 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. The outcome is the average voltage level, measured using hourly voltage data at the GridWatch device level. Column (1) tests for differences by whether a device is in a site below the median distance to the nearest injection transformer, while Column (2) tests for differences by distance, measured in 100m. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B5: Impact of transformer injection intervention on customer electricity experience

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

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

Table B6: 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. Business expenditures in the past month decreased by 0.22 SD ($98, $p = 0.049$), but reported revenues also decreased by 0.14 SD ($87, $p = 0.14$), such that there is no effect on profit. The effects on business costs furthermore do not survive False Discovery Rate (FDR) adjustment for multiple hypothesis testing (Table C8). We therefore attribute this result to statistical noise. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B7: Impact of transformer injection on household outcomes

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

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

Table B8: Heterogeneous impacts of transformer injection intervention on primary outcomes

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

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

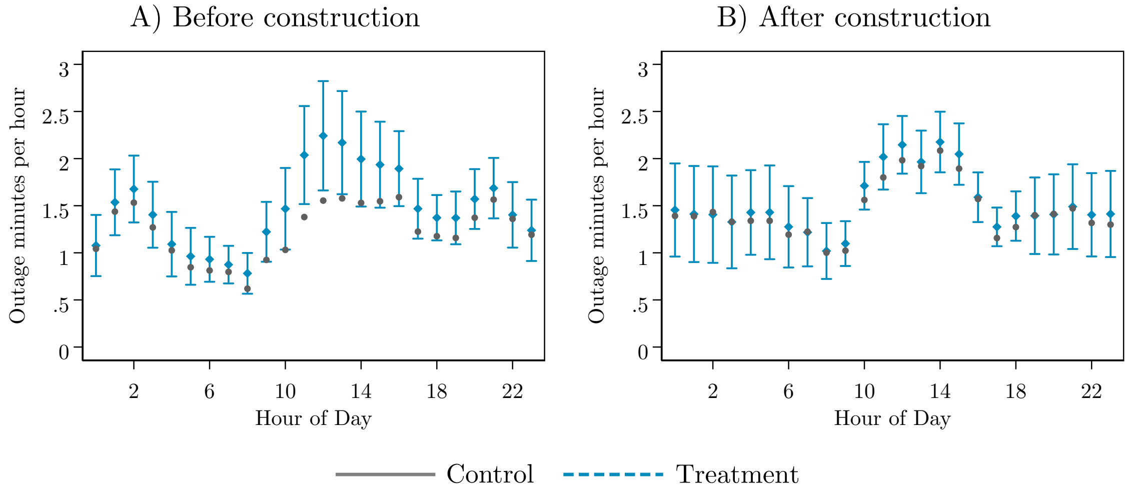
Table B9: Impacts of transformer injection intervention on voltage by baseline voltage quality

	(1)	(2)	(3)	(4)
	All sites	Below median baseline voltage	Above median baseline voltage	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

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



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

Table C1: 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table C8: Impact of transformer injection intervention on primary outcomes

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

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

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

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

This table shows the same difference-in-difference analyses presented in Table B5. Column 1 replicates the 'Post × Treat' column from Table B5. Column 2 drops two sites in Kaneshie where the construction manager SMEC indicated the new transformer was not commissioned successfully. Column 3 drops sites where our own construction monitoring activities indicated no new transformer was built in a treatment site or a new transformer was built in a control site. Column 4 instruments for observing a new transformer during the construction monitoring visits with site treatment assignment. Column 5 shows the difference-in-difference results from the main equation, by dropping geographically close control sites. We define distance by the shortest path to a treatment site, and we drop ant control site that is within 1.3 km from a treatment site, where 1.3 km is the median distance to a treatment site. Standard errors are clustered at the site level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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

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

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

Table C11: Correlations between voltage quality and primary outcomes

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

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

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)

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

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

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

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

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

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

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

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

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

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

Table D5: Impact of transformer injection intervention on business outcomes

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

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