Pre-Analysis Plan

“The Impact of Urban Power Reliability in Developing Economies: Evidence from Ghana”

RIDIE Evaluation Title: “The economics of long-term grid reliability”

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Abstract

The goal of this study is to estimate the causal impacts of power reliability on socioeconomic outcomes of households and businesses in urban Ghana. Understanding the different channels through which unreliable power impacts households and businesses has been an empirical challenge because outages in specific neighborhoods occur for a variety of reasons, which makes identifying as-good-as-random variation in outages difficult. Further, not even utilities have good information on power reliability, which poses a measurement challenge for researchers. We partner with a team of engineers who have developed a novel, low-cost sensing technology to measure outages and voltage fluctuations with high spatial and temporal resolution. We use these data to implement two quasi-experimental empirical strategies to estimate the impact of unreliable power. Criteria for prioritizing electricity access during load shedding operations on the existing power grid generate quasi-experimental variation in long-term exposure to outages, which changes discontinuously at the boundaries of areas served by electricity grid feeder lines with different priority classifications. Short-term variation in both outages and voltage stability is generated by utility investments that were quasi-randomly assigned, which facilitates a difference-in-differences design.

1. Introduction

Over the next several decades, almost all of the increase in energy demand worldwide is expected to come from developing countries, including those in Africa. Africa has witnessed significant increases in *access* to electricity, but the *reliability* of power supply, particularly in cities, remains low.[1] Electricity companies in the region are evaluating approaches to improve the reliability of their urban electricity networks. However, there is limited information on both the effect of network investments on reliability and the effect of improved reliability on socioeconomic outcomes.

Frequent outages can constrain the economic well-being of households and businesses by reducing the benefits from, and discouraging investments in, welfare-improving appliances (such as fans or refrigerators) or productive machinery. To mitigate the impacts of these outages, customers can invest in imperfect substitutes for high quality grid electricity, such as backup generators and stabilizers, which could increase operating costs, reduce productivity, or crowd out productive investments. The magnitude of these impacts and the scope of investments in substitutes is not well understood. It is important to understand these magnitudes so that electric utilities and policymakers can evaluate the impacts of improved reliability and incorporate these into decision-making about grid quality improvements.

Our primary research goal is to study the economic and socio-economic impacts of more reliable power on customers,[2] including households and businesses, and to explore the mechanisms through which these impacts may materialize.

Customers consume electricity through electrical appliances, such as refrigerators or televisions, and machinery. For customers to benefit from improved power reliability, we would first expect to see an improvement in their electricity usage through these channels, for example by operating their equipment for more hours, by purchasing more or higher quality equipment, or by spending less money on replacements for reliable grid power, such as backup generators or voltage stabilizers. We will analyze whether and how reliability affects the electricity use of firms and households through these channels to understand the mechanisms through which reliability may affect household well-being and firm performance. Importantly, we will measure not only shorter-run outcomes (e.g., immediate productivity impacts) but also longer-run outcomes (e.g., capital investment).

For households, we consider impacts on several indicators of well-being, including income, educational achievement, and health. We estimate the impacts of electricity reliability on these

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[1] The main electricity reliability issues are power outages and voltage fluctuations. Outages mean no electricity is available, while voltage fluctuations affect the quality of the electricity that is provided and can lead to improper functioning or damage of electric appliances In what follows most of our attention is on the outages dimension of reliability, though our quasi-experimental approach considering the impacts of improvements in the electricity grid will also analyze the impacts of changes in voltage fluctuations.

[2] We focus on the impacts of *improvements* of reliability in this study. In essence, we take widespread poor electricity reliability observed in Accra as the baseline and consider the impacts on reliability of improvements to the electricity grid and of being located on parts of the electricity grid that receive priority access to electricity during load shedding.

outcomes as well as several household-specific intermediate outcomes (i.e., not including the electricity usage channels described above) which might act as channels for observed improvements in our primary indicators of well-being. Intermediate outcomes we will measure include labor force participation or home enterprise, time spent studying, and improved neighborhood safety. This will allow us to explore which channels may be most important for driving any observed changes in well-being we observe, and to better understand the mechanisms through which electricity reliability may affect economic growth.

For businesses, we seek to quantify the impact of electricity reliability on measures of businesses performance and of business closure. Do firms expand or intensify production, expand employment, and invest in expanded plant or other fixed assets and/or different production technologies that rely on electricity in response to improved reliability? We measure the impact of reliability on profits and intermediate inputs such as employment, investment in electricity and power-generating capital equipment, revenues, operating costs, secondary business activities, investments in substitutes for high-quality power, and hours of operation.

There are several reasons to believe that power quality and reliability may be endogenously related to socioeconomic outcomes. For example, utilities may consider the economic importance of local businesses or the wealth of local households in determining which feeders to supply during load shedding events. Moreover, if the utility has installed and maintained the electric infrastructure more comprehensively in areas with higher levels of economic activity, more remote customers may have both lower voltage and lower socioeconomic outcomes. If this is true, simply analyzing cross-sectional variation in socioeconomic outcomes could lead to a biased estimate of the impacts of power reliability.

We measure the causal impact of power reliability using quasi-experimental variation in levels of reliability based on the electricity grid's geospatial characteristics. We use two sources of variation to isolate the causal impacts: historical variation related to the priority status of certain feeders during load shedding operations, and current variation from utility investments improving grid infrastructure. Our data come from an original socioeconomic survey, electricity sensors that we install (called GridWatch devices), the Ghana Statistical Service (GSS), as well as historical outage records, geospatial grid data, and details of proposed electricity infrastructure investments, supplied by the utility.

We are filing this pre-analysis plan before the major survey activity to collect data on household and business outcomes has begun. The survey will collect retrospective data referencing 2012-2016, when Ghana experienced significant power shortages, to understand outcomes in response to utility load-shedding operations, which is our first source of quasi-experimental variation in power quality. It will also collect baseline data at control and treatment sites for the utility infrastructure investments that are currently in progress and which form the basis for our second source of quasi-experimental variation in power quality. The survey instrument is attached as an Appendix.

2. Quasi-Experimental Designs

We employ two distinct approaches to investigate the impacts of reliability.

First, we use quasi-experimental variation in exposure to low power reliability generated by spatial discontinuities in the *load shedding operations* of the existing power grid. Second, we use quasi-randomly assigned *utility investments* designed to improve the local grid infrastructure to compare sites that benefitted from the investments to similar sites that did not.

Below we detail both empirical strategies.

Variation based on load-shedding – Priority Feeder Approach

Our empirical strategy is to exploit spatial discontinuities in households' and firms' power reliability generated by the operations of the utility when load shedding is required to balance supply and demand. This strategy – which we call the "priority feeder" approach – takes advantage of the fact that some customers may happen to be connected to a feeder that serves a priority customer (e.g., a hospital or police station) while a statistically equivalent group of neighboring customers happen to be connected to feeders that do not serve any priority customers.[3] For example, neighboring households may be statistically indistinguishable in terms of socioeconomic characteristics, but one may be quasi-randomly assigned to be served by a feeder that also serves a hospital or government ministry "down the line," leading to higher power quality for one household but not the other. Detailed geospatial infrastructure data provided by the utility allow us to identify the feeders with special classifications that serve priority customers and the boundaries between them.

Substantial variation in outages occurred during the energy crisis period of 2012-2016 (locally referred to as "Dumsor") when the utility (ECG) was forced to implement load shedding schedules. Rolling blackouts of 12 hours or more were implemented on certain distribution feeders, generating significant quasi-random cross-sectional variation in reliability. Certain feeders were designated as "exempt" from load shedding due to connections to critical infrastructure such as hospitals. All households and firms connected to these feeders would have benefited from reduced load shedding relative to neighboring households and firms connected to an "ordinary" feeder.

We define priority feeders as those that experienced fewer than 20 hours per month of load shedding outages during the Dumsor period, using historical outage data from ECG Situational Reports which log all outage events on medium voltage and high voltage transmission lines. This set of priority feeders aligns well with the set of feeders identified in conversations with ECG as being exempt from load shedding operations.

We will use GSS data from years prior to Dumsor (notably the 2010 census) to test for pre-treatment balance of observables, which is the identifying assumption for this approach.

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[3] Electricity customers receive electricity through low-voltage lines connected to electricity transformers, which convert electricity from medium-voltage "feeder" lines to a voltage level suitable for customers. A given feeder line provides electricity for all customers in the electricity network whose low-voltage connections are connected to transformers on the feeder line.

For the priority feeder approach, we will survey firms and households that are located near the boundaries of priority and ordinary feeders, identified using detailed geospatial data on grid infrastructure. Neighboring households and firms in boundary areas served by different types of feeders are likely to be similar. We identify three types of sites: priority-only GSS enumeration areas (EAs) where all customers in the EA are served by a priority feeder, ordinary-only EAs that border EAs served by a priority feeder, and EAs served by both types of feeders. For households and firms surveyed in the latter type of EA, we will use GPS location information to determine ex post whether they are served by an exempt or an ordinary feeder, and verify this using household reports of outage experiences.

Using EAs as survey sites for the priority feeder evaluation has several advantages. First, we are able to use GSS data to conduct baseline balance tests across EAs, in order to test whether neighboring households or firms were statistically similar prior to the Dumsor period. Second, EAs are recognized and well-understood sampling areas and our survey implementation partners at the University of Ghana are confident in being able to conduct household and firm sampling within EA boundaries in Accra.

Variation based on quasi-random assignment of utility investments – LV Bifurcation Approach

The Millennium Challenge Corporation (MCC) is currently working with the Government of Ghana to invest over $100 million in the electricity system through Ghana Compact II[4]. One of the activities under the Compact is low voltage (LV) line bifurcation, under which new transformers are added to the grid. New transformers are designed to reduce the number of overloaded transformers, thereby reducing outages related to blown fuses, and reduce the distance between customers and the transformer, thereby improving voltage quality.

The firm that is overseeing the engineering design and supervising the construction (SMEC) has agreed to conduct line bifurcation by adding a transformer in certain pre-selected locations. Through extensive conversations with the firm and MCC we have concluded that these locations were selected without any information about local economic conditions. The firm used engineering guidelines to select locations, but these were imperfectly adhered to, generating quasi-random variation in where transformers were placed. Based on our conversations, though other criteria were considered the main engineering guideline used by the firm was to identify parts of the grid over 200m from the nearest transformer. We have been provided a list of line bifurcation locations, and randomly selected "control" service areas from a pool of sites located at least 200m from existing transformers in the same electricity districts where the line bifurcation investments are taking place, mirroring the criteria for line bifurcation site selection. We will implement a difference-in-difference design, comparing outcomes in grid service areas around injection sites with outcomes in control sites.

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[4] The original Compact called for $308 million of investment, but $190 million was removed by MCC from grant totals in response to the Government of Ghana's decision in 2019 to terminate the concession agreement between the electricity utility and a private operator.

There are two testable requirements. First, the control and treatment sites must exhibit similar trends over time in terms of reliability and the outcome variables prior to the line bifurcation. We have been collecting GridWatch outage data in the relevant sites for more than a year, and using these data we have tested and confirmed that indeed there have been no detectable differences in power quality across the treatment and control sites over the pre-period. Second, the sites must not have been chosen on any factors correlated with the outcomes of interest, which in our case are economic indicators. This would be a concern if, for example, the engineering firm incorporated economic indicators such as income across all the different transformers when making their decision about where to inject new transformers. Through extensive conversations with the firm, we feel confident that this is not the case. Our understanding is that the firm did not even have access to economic information when they were making their injection decisions. Further, we will be able to assess whether project completion is correlated with economic outcomes by comparing results where we use an indicator variable, based on the original sites targeted for line-bifurcation[5], to instrument for project completion (essentially estimating the local average treatment effect coefficients) to results where we do not instrument with the original site indicator variable. In addition, we will conduct a baseline survey in treatment and control locations which will allow us to test for balance across socioeconomic indicators. We will further test for baseline balance using data from the deployment of GridWatch devices to treatment and control sites. Combining data from device deployment and the baseline socioeconomic survey will further allow us to test for parallel trends in pre-treatment outcome variables.

We therefore feel confident that the Difference-in-Difference (DD) approach will be rigorous and that any differences in power quality or economic outcomes between control and treatment sites will be caused by the line bifurcation activities.

3. Data

Primary Data

We will administer a survey to 2,500 households and 2,500 businesses that are connected to the electricity grid in Accra. The survey will gather a broad set of characteristics on present-day outcomes for households and firms in both priority feeder and line bifurcation survey locations. Some respondents will also answer a smaller set of questions asking them to recall information from the Dumsor crisis period, from 2012-2016. These recall questions will only be asked to respondents who are at least 25 years old currently (in 2021) and have been at the same location since at least December of 2014. Recall questions will be asked for all eligible respondents in priority feeder sites and a random quarter of eligible respondents in line bifurcation sites, so we can test whether outcomes during Dumsor are similar for control households near to priority feeders and farther away.

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[5] Several sites originally selected for line bifurcation injections have already been changed, and other sites currently identified as injection sites may not receive injections.

We will administer the survey to 2,000 firms and households in the line bifurcation sites, evenly dividing the sample across treatment and control sites. For these sites, we will conduct both a baseline survey before the completion of the line bifurcation injections and an endline survey around 2 years afterward.

For the priority feeder approach, we will survey 3,000 firms and households that are located near the boundaries between priority and ordinary feeders. We aim to survey an equal number of respondents in priority feeder (treatment) sites and ordinary feeder (control) sites. For priority feeder sites we will only administer one survey round, which will include questions about the present and the Dumsor crisis period.

In all survey sites, enumerators will follow a random walk protocol to identify respondents to approach for participation in the survey. Enumerators will begin at the site centroid and pick a random direction to begin walking, and approach every fourth household (every third in smaller sites) or firm they encounter along their path until they have reached the target sample size for households and firms for the site. Each random walk will specifically target either households or firms.

GridWatch Data

We have deployed GridWatch devices to 3 households or firms in each line bifurcation treatment and control site. The multiple devices allow us to use machine learning methods to detect outages and voltage fluctuation at a very fine temporal level in a private cloud-based server. Data from these devices allow us to measure reliability indicators including count of outages, average and total outage duration, and frequency of voltage fluctuations. We will use these data to test for pre-trends in treatment and control sites and to estimate the effect of the line bifurcation injections on electricity reliability, which is the first stage of our analysis of the impacts of reliability of socioeconomic outcomes under the line bifurcation quasi-experimental approach.

There are no GridWatch devices deployed in the priority feeder sites, as the reliability differences we leverage for this quasi-experimental approach are historical.

Secondary Data

- We use data from the Ghana Statistical Services (GSS) to choose EAs to draw our priority feeder site samples and test for balance across household characteristics. Specifically, we test for balance using data from the 2010 Census.
- We use data from SMEC on line bifurcation locations to identify treatment and control sites for the line bifurcation approach, including revisions to these site locations in accordance with project updates. We use data on project completion to identify the timing of treatment in line bifurcation injection sites.
- We use ECG data for grid and priority feeder identification. We have compiled detailed geospatial data on the electricity grid and have worked closely with ECG engineers to identify which feeders receive priority for electricity during load shedding events now and during Dumsor. We also use historical data from ECG on outages by feeder to measure differences in electricity reliability by feeder over the period from 2012-2020.

4. Analysis

We conduct separate analyses for our priority feeder and line bifurcation samples. Many outcomes are specific to firms or to households, though outcomes related to electricity use and appliance ownership and use apply to both samples. We separately analyze outcomes for firm and household respondents, and control for whether the respondent's household and business are in the same location/structure. Thus for any given specification we will run multiple analyses for our different sub-samples. The set of outcome, treatment, and control variables is described in more detail in section 5 of this pre-analysis plan.

Priority Feeder Approach

Empirical Specification

We exploit quasi-random variation in reliability by selecting firms and households that are near each other and have similar observable characteristics but are served by feeders with different priority status.

Broadly, outcome data include measures that are contemporary to the time of the survey and measures from a previous period when power outages occurred more frequently (the Dumsor crisis). Reliability is measured both discretely (i.e., served by a priority or ordinary feeder) and with a continuous metric of the observed outage hours of the firm/household's feeder.

We estimate the causal impact based on cross-sectional variation (using the quasi-experimental assignment of priority status for identification):

$$Y_{ift} = \alpha \quad + \ \beta PRIORITY_{if} + \sum \theta X_{ift} + \varepsilon_{ift}$$

where Y_{ift} measures the outcome variable for household or firm *i* on feeder *f* during period *t*, X_{ift} is a vector of control variables, and $PRIORITY_{if}$ is a measure of power reliability. As we describe below, we will include both discrete and continuous metrics of reliability. β is the parameter of interest and measures the impact of receiving more reliable power from a priority feeder on the outcome variable. We will run this analysis pooling the data from the present and the period of the Dumsor crisis as well as separately for each period.

Definition of Treatment

Treatment is defined at the feeder level, and individuals are matched to a feeder using their location on the electricity grid. We define priority feeders as those that experienced fewer than 20 hours per month of load shedding outages during the Dumsor crisis period, using historical outage data from ECG Situational Reports which log all outage events on medium voltage and high voltage transmission lines. This set of priority feeders aligns well with the set of feeders identified in conversations with ECG as being exempt from load shedding operations, as a function of important pieces of infrastructure the feeders serve. We will also consider ECG "exempt" feeder designation as an alternative definition of treatment. The binary measures of treatment are indicators of whether the feeder was prioritized for low load shedding outages during the Dumsor period. We also create several continuous measures: (1) the average monthly hours of load shedding in 2014-2016 and just in 2015 (the peak of Dumsor), and (2) the count of load shedding events in the above periods.

LV Bifurcation Approach

Empirical Specification

For the LV bifurcation quasi-experimental approach, we will use a difference-in-difference (DD) design. Intuitively we will compare customers who are within a very similar distance from an existing transformer (e.g., between 200-600 meters), and thus on average will have similar characteristics and power quality at baseline, except that some of these households will have their line bifurcated with a transformer injection and thus may experience higher power reliability and quality in the follow-up period. We implement the DD strategy by estimating the following regression equation:

$$Y_{ist} = \beta_0 + \beta_1 TREAT_s + \beta_2 POST_t + \beta_3 TREAT_s * POST_t + \sum \theta X_{ist} + \varepsilon_{ist} \qquad (4)$$

To test for a “first stage”, we estimate the model above where the outcomes are monthly outage frequency, outage duration, and voltage fluctuations, and there are limited covariates X_{ist} using only data from before the LV bifurcation work was completed in a given site. This specification is run at the level of survey sites s, as this is the level at which GridWatch devices allow us to measure electricity reliability.

To test for reduced-form impacts, Y_{ist} measures the outcome for firm or household i in site s in period t and X_{ist} is a vector of control variables. We will include the same control variables in all regressions. $TREAT_s$ is an indicator of whether the customer is in a site selected for bifurcation and $POST_t$ is an indicator for whether the customer is being observed after the line bifurcation work has been completed. The coefficient of interest is β_3, which measures the effect of treatment – being in a site selected for bifurcation after the bifurcation work has been completed. This coefficient is the estimated causal impact of bifurcation eligibility (not necessarily completion as it is possible not all selected sites will receive line bifurcation improvements) on the outcome.

By combining this estimate with metrics of the first-stage impact of bifurcation on power reliability and quality, we will estimate the causal effect of power reliability or power quality on the outcome.

Definition of Treatment

In addition to defining treatment as a binary indicator for being selected to receive a line bifurcation injection, we will also define a continuous treatment variable using the change in reliability following the injection, as measured by GridWatch devices in treatment and control sites. We will isolate the causal effect of changes in reliability through an instrumental variable (IV) approach using line bifurcation eligibility status as an instrument for the change in electricity reliability. Similarly, if we observe differences in the sites that were targeted for line bifurcation work and the sites that actually received a new transformer, we will also run regressions where the treatment is completion of a line bifurcation project, and we will use line bifurcation eligibility status as an instrument for actually having a completed line bifurcation in the site.

Correction for Inference Based on Multiple Hypothesis Testing

There could be two sources of false positives: (1) those driven by sampling variation and (2) those driven by the fact that we are testing against the null hypothesis for multiple outcomes that could be impacted by reliability. We will present two sets of p-values. For readers with an a priori interest in a specific outcome, we present the standard "per-comparison" p-value. For readers interested in the set of outcomes, we adjust for multiple hypothesis tests by accounting for the possibility that some true null hypotheses will be rejected. We will present the false discovery rate (FDR)-adjusted q-value that limits the expected proportion of rejections within a hypothesis that are Type I errors (i.e., false positives). We will follow the approach to FDR analysis adopted in Casey et al. (2012) and the references cited therein (e.g., Anderson 2008). We will present FDR-adjusted q-values for each of our primary outcomes within each outcome group, as well as for each other outcome variable of interest.

Testing Threats to Identification

Common Shocks to Treatment and Control

For the LV bifurcation approach, we will statistically test if trends in outcomes are parallel between injection sites and control sites in the months prior to treatment. We will use data from GridWatch sensors to test for parallel trends in measures of electricity reliability at a fine temporal level. We will use data from our sensor deployment surveys and baseline socioeconomic survey to test for parallel trends in outcome and control variables. In addition, we will conduct falsification tests with false (early) treatment of improved reliability.

For the priority feeder approach, we will conduct balance tests using data from the 2010 Census (before the Dumsor crisis period) to compare characteristics of neighboring enumeration areas served by priority and ordinary feeders.

Treatment Affecting Selection into Sample

The Dumsor crisis (and any other variation in historical outages) may have induced households or firms to relocate to a location with different power reliability. Since this decision is endogenous to our treatment variable, comparing the outcomes of households that now (post-treatment) live in areas served by priority feeders to households that live in nearby areas served by ordinary feeders may be biased because those households may differ in unobservable characteristics that affect outcomes. For example, consider two households that were similar in observable demographic characteristics prior to Dumsor but one household (unobservably to us) planned to start an at-home business that requires constant power during the day while the other did not. The first household may have moved during Dumsor to a neighborhood with more reliable power. If we compare the post-Dumsor incomes, a simple comparison would attribute all of the income difference to reliability when some of the difference is due to unobserved productivity differences across the households. Put differently, treatment could affect selection into our sample, which is a potential threat to identification.

Selection might affect our priority feeder sample in two ways. First, the set of households and firms currently located in priority and ordinary feeder areas may differ in unobservable ways, biasing our estimates of the effect of being on a priority feeder on contemporary outcomes. Second, our analysis of the impacts of being on a priority feeder during the Dumsor crisis uses recall from households and firms that remain in the same location as they were in during the Dumsor crisis. This set of respondents may not be representative of all households and firms that were in our priority and ordinary feeder sites during the Dumsor crisis, potentially biasing our results. Perhaps more importantly, the selection process for these respondents may differ by priority status, if for example respondents less reliant on electricity are those more likely to have remained in ordinary feeder sites since Dumsor, while the opposite could be true in priority feeder sites.

We cannot directly test for differences in unobservables, but we can test for whether neighborhoods with different types of feeders have differential rates of turnover in tenancy. We use survey answers from the Location Recall section of our survey to test for differential turnover between priority and ordinary feeder locations. We will conduct individual t-tests and a joint F-test for differences in: (1) respondent lived in same location during the Dumsor crisis, (2) adjacent neighbors have the same occupants as during the Dumsor crisis, and (3) adjacent neighbors' primary business industries.

In the event that our full sample rejects the joint F-test, we will explore modeling approaches to deal with endogenous decisions about location and entry/exit.

For the LV bifurcation approach, differential selection may bias our estimates if respondents choose to relocate based on changes in power quality and this generates attrition in the endline. To address this we will compare attrition across treatment and control sites between baseline and endline and apply Lee bounds to evaluate how differences in attrition may affect study estimates.

Spillovers and SUTVA Assumption

It is possible that the adjacency of treatment and control neighborhoods can create spillover effects from firms in the treatment to the control group. Namely, the local business outcomes for control firms could be impacted by treatment if poor reliability in control neighborhoods induced some customers to purchase from firms in nearby treatment neighborhoods. For example, if two adjacent neighborhoods both have stores that sell retail electronics, outages that force one store to close during the week may induce consumers to shop at the store in the neighborhood with reliable power. Our estimated treatment effects will be biased upwards for industries with large potential for demand-side substitution.

The potential for spillovers is larger in our priority feeder approach as the priority (treatment) and ordinary (control) sites included in the analysis are by design adjacent to each other, and because the Dumsor crisis resulted in very large long-term differences in reliability between these areas. Spillovers are less of a concern for the line bifurcation approach as no line bifurcation injection (treatment) sites and control sites are adjacent to each other and because we do not expect the reliability changes to be very large, but electricity improvements in treatment sites could potentially be significant enough to draw customers for nearby control sites.

In order to test for spillovers, we will first separately estimate the impact of improved power reliability on businesses in industries that may be more or less susceptible to "demand-side" spillovers. For example, such spillovers may be more prevalent in retail electronics than personalized services such as hairdressing and seamstresses. We will test for differences in estimated impacts for industries where there are a priori reasons to believe that spillovers are more and less likely to exist, and use these differences to assess the potential role of demand-side spillovers. Second, we will use data collected from control, non-adjacent sites to try to estimate the extent of the spillovers.

5. Outcomes and Variable Construction

We consider 5 sets of variables in our analyses. First, measures of electricity reliability are used to construct continuous treatment variables and to measure "first stage" impacts of binary treatment. Next we construct electricity-related outcome variables that apply to both households and firms, including measures of electricity use, reliability protection equipment, and electric appliances. We then consider separate sets of variables that apply only to households or only to firms. These variables include both outcomes of interest as well as control variables that we will include in our analyses. Finally, we consider an additional set of variables which might affect the estimated treatment effect and which we will separately include in our analyses as controls in additional specifications.

Construction of Indices

In several cases we combine information from several variables in our socioeconomic survey into a single index. When constructing indices, we will normalize each component variable such that the control group has mean zero and unit variance, and thereafter we will construct the index by summing each component variable and then re-normalizing (the mean effects approach). Note that we will exclude any variables with zero (or very close to zero) variance since these do not contribute any information to the analysis. Furthermore, if a pre-specified variable is missing for more than 30% of possible observations collected in the follow-up surveys, we will drop it from inclusion in the index. We cannot anticipate why a particular variable will be missing so frequently, and believe such cases will be rare, but in such events where it warrants exclusion, we shall also explore these reasons in the analysis.

Within each outcome family, there are outcomes at different levels of aggregation, ranging from specific variables to indices that combine data from multiple variables. Due to the novelty of many of these measures, some of the groupings are speculative. We will therefore report measures of index quality and coherence in the appendix, for example, by examining the correlation patterns of measures within each index. Depending on the index quality, we may also perform additional analyses, for example, presenting results with alternative groupings of outcomes. For completeness and transparency, in the appendix, we will also present estimated impacts for all specific outcomes individually, including those used to construct each of the indices.

Missing Appliance Values

For a subset of electrical appliances and alternative energy sources, respondents in the survey will be asked the value of those appliances. When the respondent does not know the value or refuses to answer, for our analyses we will impute the value using the median of responses, except when more than 30% of respondents do not provide a value for a particular item. In this latter case, we will remove that item from construction of our indices measuring appliance values.

Reliability Treatment Measures

We will estimate the impact of line bifurcation transformer injections on quality and reliability of power by using GridWatch sensors to measure resulting changes in outage frequency and duration and voltage quality in areas that receive the injections and in control sites. We will complement these data with household and firm recall measures of outages and voltage fluctuations. The effect of line bifurcations on reliability measures serves as the first stage for our analysis of the impact of improved reliability on socioeconomic outcomes under the line bifurcation approach, rather than as a final outcome of interest.

In the priority feeder sites, differences in measured reliability reflect the treatment of interest, so will not be measured as an outcome. We will not have GridWatch sensors at the priority feeder sites, so in those areas we will use data from historical ECG situational reports to construct continuous treatment measures. The situational reports include data on outages and outage duration by feeder from 2012 to 2020. The surveys will also ask respondents about their experiences during the period of the Dumsor crisis.

Table A: Grid Reliability Variables

ID	Variable	Unit	Type	Description	Source
G1a	Outage frequency	Firm/ HH	Count	Number of outages in the past 30 days	Survey
G1b	Dumsor outage frequency	Firm/ HH	Count	Number of outages in an average month between 2012-2016	Survey
G1c	Outage frequency	Feeder/ Site	Count	Number of outages in an average month in 2020, in 2015, and between 2012-2016	ECG Situational Reports
G1d	Outage frequency	Site	Count	Number of outages in the past 30 days, Number of outages in an average month in 2020	GridWatch
G2a	Average outage duration	Firm/ HH	Hours	Average duration of power outages in the past 30 days	Survey

G2b	Dumsor outage duration	Firm/ HH	Hours	Average outage duration between 2012-2016	Survey
G2c	Outage duration	Feeder/ Site	Hours	Duration of outages in an average month in 2020, in 2015, and between 2012-2016 Maximum monthly outage hours	ECG Situational Reports
G2d	Average outage duration	Site	Hours	Average duration of power outages in the past 30 days, and average outage duration in 2020	GridWatch
G3a	Longest outage	Firm/ HH	Hours	Duration of longest outage in past one year	Survey
G3b	Dumsor longest outage	Firm/ HH	Hours	Duration of longest outage from 2012-2016	Survey
G4a	Voltage fluctuations	Firm/ HH	Hours	Average hours per day of voltage fluctuations in past 30 days	Survey
G4b	Voltage fluctuations	Site	Hours Hours Hours	Average hours per day of voltage fluctuations in past 30 days and in 2020 Hours per day of high voltage Hours per day of low voltage	GridWatch
G5	Streetlight functioning	Firm/ HH	Proportion	Share of last 7 nights that street lighting functioned properly	Survey

Electricity-Related Variables – Firms and Households

Customers consume electricity through electrical appliances, such as refrigerators or televisions, and machinery. For customers to benefit from improved power reliability, we would first expect to see an improvement in their electricity usage through these channels. We will evaluate impacts on a variety of electricity-related outcomes that are relevant to both firms and households, as well as some that are relevant to households only. A few of these variables are primary outcomes of interest in and of themselves, but all electricity-related variables are of further interest as potential mechanisms for the impact of improved reliability on our main socioeconomic outcomes of interest.

Table B: Electricity-Related Variables

ID	Variable	Unit	Type	Description
Primary Outcomes – Firms and Households				
E1	Willingness to pay for improved reliability	Firm/ HH	Value Value Value	Willingness to pay for perfectly reliable electricity connection Willingness to pay for specific reliability issues, calculated as WTP for perfectly reliable electricity connection minus WTP for reliable electricity with one specific issue Willingness to pay for generator
E2a	Value of reliability defensive investments	Firm/ HH	Value	Sum of values of defensive investments: TV guards, fridge guards, stabilizers, inverters, other surge protectors, phases (discounted) Value of multi-phase system
E2b	Dumsor value of reliability defensive investments	Firm/ HH	Value	Sum of values of defensive investments held during Dumsor, including investments held and not replaced (discounted) Value of multi-phase system

E3	Value of non-defensive capital investments – electric appliances	Firm/ HH	Value	Value of electric appliances owned at location, calculated as sum of value of appliances in each type
E4a	Capital investments – alternative energy sources	Firm/ HH	Dummy Value	Any alternative energy source (generator, solar panel, wet cell battery) Total value of alternative energy sources
E4b	Dumsor capital investments – alternative energy sources	Firm/ HH	Dummy Value	Any alternative energy source (generator, solar panel, wet cell battery) from 2012-2016 Total value of alternative energy sources held in Dumsor.
Primary Outcomes - Households				
E5a	Value of convenience appliances	HH	Value	Convenience appliances: TV, fans, AC, blow dryer, TV receiver, DVD/CD player, hair straightener, heater, kettle, microwave, radio, rechargeable torch, stereo/music system, tablet
Primary Outcomes - Firms				
E5b	Value of non-electric capital investments	Firm	Value	Aggregate value of five most valuable current machines and equipment used for the business that do not require electricity
E5c	Dumsor value of non-electric capital investments	Firm	Value	Aggregate value of five most valuable machines and equipment used for the business during the Dumsor crisis that do not require electricity
Secondary Outcomes and Mechanisms – Firms and Households				
E6a	Appliance protection	Firm/ HH	Count Index	Defensive appliances held: TV guards, fridge guards, stabilizers, inverters, other surge protectors, phases Share of TVs plugged into TV guard Share of fridges plugged into fridge guard Share of major appliance types plugged into surge protectors Have multi-phase system
E6b	Dumsor appliance protection	Firm/ HH	Count	Count of defensive appliances during Dumsor: TV guards, fridge guards, stabilizers, inverters, other surge protectors, phases
E7	Phase switching	Firm/ HH	Z-score Value	Frequency of switching phases Cost of installing phase system
E8	Grid electricity spending	Firm/ HH	Value	Total spent in past 3 months on grid electricity
E9	Expenditures on burnt or broken appliances	Firm/ HH	Value Dummy	Amount spent to repair appliances damaged due to electricity issues in last 12 months Any burnt or broken appliances not repaired or replaced
E10	Outage backup power	Firm/ HH	Index	Frequency of generator or wet cell battery use during an outage Share of appliance types owned using generator or solar panel during an outage
E11a	Non-electricity fuel consumption	Firm/ HH	Index	Frequency of generator use Frequency of wet cell battery use Count of alternative lighting sources used (kerosene/paraffin, candle, torch/flashlight, solar lantern, cellphone, fire) Count of alternative fuels used in past 3 months (wood, charcoal, gas, kerosene/paraffin, crop residue, sawdust, animal waste)
E11b	Spending on non-electricity fuel	Firm/ HH	Value	Spending on generator fuel and maintenance in past 3 months

				Spending on solar panel maintenance in past 3 months Spending on alternative fuels on average each month by type (wood, charcoal, gas, kerosene/paraffin, crop residue, sawdust, animal waste)
E11c	Dumsor non-electricity fuel consumption (2012-2016)	Firm/ HH	Index	Frequency of generator use Frequency of wet cell battery use Count of alternative lighting sources used (kerosene/paraffin, candle, torch/flashlight, solar lantern, cellphone, fire) Count of alternative fuel types used (wood, charcoal, gas, kerosene/paraffin, crop residue, sawdust, animal waste)
E12a	Outage awareness	Firm/ HH	Proportion	Proportion of outages in the past year for which respondent was aware in advance
E12b	Dumsor outage awareness	Firm/ HH	Proportion	Proportion of outages from 2012-2016 for which respondent was aware in advance
Secondary Outcomes and Mechanisms - Households				
E13a	Use of cooling appliances	Firm/ HH	Hours	For ACs and fans, take sum of hours per day appliances were turned on by appliance type
E13b	Use of lightbulbs	Firm/ HH	Hours	Total hours per day lightbulbs are turned on (sum across lightbulbs)
E13c	Use of convenience appliances (TV)	Firm/ HH	Hours	Hours per day TV is turned on

Firm Variables

The table below describes firm-specific outcome and control variables used in our analyses.

Table C: Firm Variables

ID	Variable	Unit	Type	Description
Primary Outcomes				
F1	Profit	Firm	Value	Total profit in past 1 month, not including any income paid to business owner
F2	Revenue	Firm	Value	Total revenue in past 1 month
F3a	Costs	Firm	Value	Monthly rent to occupy premises (if renting) + labor expenses + inventory and materials expenses + grid electricity spending in past 3 months divided by 3 + spending on alternative energy sources in past 3 months divided by 3 + spending on other fuels in past month
Secondary Outcomes and Mechanisms				
F3b	Labor expenses	Firm	Value	Total paid in wage/salaries and other benefits in past 1 month
F3c	Inventory and materials expenses	Firm	Value	Total paid for inventory and materials in past 1 month
F4a	Number of workers	Firm	Count	Number of men and women currently engaged by this business
F4b	Share of male workers	Firm	Proportion	Number of men / total number of workers
F4c	Share of full-time workers	Firm	Proportion	Number full-time / total number of workers
F4d	Dumsor number of workers	Firm	Count	Number of men and women engaged by this business in June 2015
F4e	Dumsor share of male workers	Firm	Proportion	Number of men / total number of workers

F5a	Hours open per day	Firm	Hours	Hours open on average day
F5b	Open during non-daylight hours	Firm	Dummy	Open before 6:30am or after 6:30pm
F5c	Dumsor hours open per day	Firm	Hours	Hours open on average day in June 2015
F5d	Dumsor open during non-daylight hours	Firm	Dummy	Open before 6:30am or after 6:30pm in June 2015
F6a	Temporary firm responses to reliability issues in past year	Firm	Index Index	Response types index: Switch to alternative energy source; Reduce work or change work; Stop work; Postpone work; Switch to different tools, machines, or labor; Switch to different business activities; Reduce labor; Other responses Response intensity index: Days of alternative energy use in past 1 month during outages, by alternative energy source; Days stopping or postponing work in past 1 month; Percentage of business hours stopping work
F6b	Permanent firm responses to reliability issues in past year	Firm	Index	Substitute to non-electric tools or machines; Substitute to more labor; Change industry/business; Purchase generator; Purchase other alternative energy source; Always use generator during business hours; Move to new location
F6c	Dumsor temporary firm responses to reliability issues from 2012-2016	Firm	Index	Switch to alternative energy source; Reduce work or change work; Stop work; Postpone work; Switch to different tools, machines, or labor; Switch to different business activities; Reduce labor; Other responses
F6d	Dumsor permanent firm responses to reliability issues from 2012-2016	Firm	Index	Substitute to non-electric tools or machines; Substitute to more labor; Change industry/business; Purchase generator; Purchase other alternative energy source; Always use generator during business hours; Move to new location
F7	Index of qualitative assessments	Firm	Index	Redefine variables so higher values indicate worse outcomes/greater constraints: Perceived safety in area Importance of electricity as obstacle to business Belief that Dumsor is back Expected reliability one year from today Importance of finance/access to credit as a business obstacle
F8	Estimated revenue impact of reliability	Firm	Value	(Estimated revenue in past 1 month with no reliability issues) – (Actual total revenue in past 1 month)
F9	Financial and credit health of firm	Firm	Value Dummy	Total value of outstanding loans Application for any loans in past 12 month

Household Variables

The table below describes household-specific outcome and control variables used in our analyses.

Table D: Household Variables

ID	Variable	Unit	Type	Description
Primary Outcomes				
H1	Household income	HH	Value	Sum of incomes from any source for all household members (age >15) converted to monthly

Secondary Outcomes and Mechanisms				
H2a	Labor force participation index	HH	Proportion	Any job outside of the home or household enterprise for which they were paid in last 7 days (share of age >15)
H2b	Dumsor labor force participation index	HH	Proportion	Any job outside of the home or household enterprise for which they were paid around June 2015 days (share of age >15 at the time)
H3a	Value of house as measure by rent	HH	Value	Monthly rent to occupy premises (if renting)
H3b	Dumsor value of house as measure by rent	HH	Value	Monthly rent in June 2015
H4	Household education	Individual	Years	Highest education completed, equivalent value in years (for household children)
H6a	Index of qualitative assessment of home activities	HH	Index	Redefine variables so higher values indicate worse outcomes/greater constraints: Perceived safety in area Loss or perishable foods due to reliability issues Risk of health issues due to reliability issues Loss of perishable refrigerated medications due to reliability issues Belief that Dumsor is back Expected reliability one year from today
			Index	Sub-Index with same variables available for Dumsor
H6b	Dumsor index of qualitative assessment of home activities	HH	Index	Loss or perishable foods due to reliability issues Risk of health issues due to reliability issues Loss of perishable refrigerated medications due to reliability issues
H7	Household health	HH	Index	Total household days stopped usual activities because of illness or injury in past 2 weeks, per household member Total spending on health care in past 2 weeks, per household member
H8	Light for reading or studying	HH	Index	Hours per day lightbulbs used for reading or studying (sum across lightbulbs) Share of hours per day reading or studying with lightbulbs vs. other light sources (kerosene/paraffin, candle, torch/flashlight, solar lantern, cellphone, fire)
H9a	Dirty cooking fuels	HH	Index	Cooking fuels/energy sources used in past 3 months (wood, charcoal, crop residue, sawdust, animal waste)
H9b	Dumsor dirty cooking fuels	HH	Index	Cooking fuels/energy sources used (wood, charcoal, crop residue, sawdust, animal waste)

Potential Control Variables

The following table includes control variables we may include in our analyses.

Table E: General Control Variables

ID	Variable	Unit	Type	Description
C1	Survey site fixed effects	Firm/ HH	Dummy	Dummy for each survey site
C2	Gender of respondent	Indiv	Dummy	1 if female
C3	Age of respondent	Indiv	Years	Age in years
C4	Education of respondent	Indiv	Years	Equivalent value in years of highest level of education completed

C5a	Meter	Firm/ HH	Dummy	Pre-paid vs. post-paid meter
C5b	Shared meter users	Firm/ HH	Count	Number of meter users if meter is shared
C5c	Meter payment	Firm/ HH	Dummy	1 if pay meter directly
CF1a	Respondent is owner	Firm	Dummy	Respondent is an owner
CF1b	Respondent is main manager	Firm	Dummy	Respondent is the main manager
CH1	Household adults	HH	Total	Total household members >=18 years old
CH2	Household children	HH	Total	Total household members <18 years old

Selection-Related Variables

The following table includes variables we will use to test for possible selection of respondents in treatment and control sites.

Table F: Selection-Related Variables

ID	**Outcome**	**Unit**	**Type**	**Description**
F1	Years in the structure	Firm/ HH	Years	Years and months since household/firm first moved into the survey location structure
F2	Years of electricity at location	Firm/ HH	Dummy Years	Electricity since respondent moved in Years and months since location was connected to electricity grid
F3	Turnover in neighboring location occupants since Dumsor	Firm/ HH	Proportion Proportion Proportion	Share of neighbors business today Share of neighbors business Dumsor Share of neighbors with same occupants today as during Dumsor

References

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