Leveraging Technology to Improve Utility Cost Recovery*

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Abstract

We study the effects of a technical intervention in Karachi, Pakistan – converting bare distribution wires to aerial bundled cables (ABCs) – that was intended to prevent illegal grid connections and improve utility cost recovery. Theft-resistant cables reduced losses. This occurred primarily through decreases in unbilled consumption, with the number of formal utility customers and their billed consumption both increasing. Load shedding outages decreased. In areas with these cables installed, consumers have more appliances and higher electricity-related expenditures. Revenue recovery rose, but consumers' billing-related complaints also increased.

Keywords: Electricity, Infrastructure, Losses
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1 Introduction

Electricity service quality in developing countries is substantially worse than in developed countries, and research has demonstrated that poor quality affects both firms (Rud, 2012; Fisher-Vanden, Mansur and Wang, 2015; Allcott, Collard-Wexler and O'Connell, 2016; Fried and Lagakos, 2022) and households (Burlando, 2014; Chakravorty, Pelli and Ural Marchand, 2014; Carranza and Meeks, 2021; Meeks et al., 2023). Prior literature argues that poor service quality stems from electricity distribution companies' inability to recover the full cost of services delivered due to high subsidies, bill non-payment, and electricity theft (Burgess et al., 2020). Although previous research addresses two of these contributors to low cost recovery – subsidies (McRae, 2015b) and bill non-payment (Jack and Smith, 2020) – little exists on theft and the resulting unbilled consumption.

We study the effects of a technical intervention in Karachi, Pakistan that made distribution lines theft-resistant and, in doing so, aimed to reduce unbilled consumption. Unbilled consumption occurs when individuals cannot be excluded from accessing the infrastructure and its associated services, and transpires through meter tampering, illegal connections that bypass meters, and billing irregularities (with meter readers often complicit) (see, e.g., Alam et al., 2004; Jamil, 2018; Abdollahi et al., 2020; Savian et al., 2021). The upgrade that we study consisted of converting bare low voltage distribution wires to aerial bundled cables (ABCs), which are twisted, insulated cables that prevent connections that bypass meters.[1] This technical solution contrasts with incentive-based interventions with similar goals of improving utility cost recovery.[2]

Available for approximately half a century, ABCs are common in Europe, Japan, South Korea, and parts of the United States and Australia, among other high income countries (La Salvia, 2006).[3] The technology, however, is less common in South Asia and

[1]Given this conversion was implemented with the specific intent of reducing theft, we use the terms ABCs and theft-resistant cables interchangeably.

[2]For example, existing research addresses pricing reforms implemented in developing countries (McRae, 2015a; McRae and Meeks, 2016; Alberini, Bezhanishvili and Ščasný, 2022; Beyene et al., 2022*a*).

[3]Locating distribution lines underground is often optimal, but it is the most expensive option and geo-

Africa, with South Africa being an exception (La Salvia, 2006). Bare wires, the lower-cost technology, were historically the default in many developing countries (Agarwal, Mukherjee and Barna, 2013), but they are susceptible to illegal connections. In the absence of ABCs, utilities must regularly inspect, detect, and remove illegal connections, with nothing preventing illegal re-connections thereafter. More recently, utilities in low and middle income countries such as Brazil, India, Iran, Mexico, and Pakistan have replaced bare wires with ABCs specifically to reduce electricity theft (La Salvia, 2006; Agarwal, Mukherjee and Barna, 2013; Abdollahi et al., 2020; Regy et al., 2021; NEPRA, 2022).

Theft is a major contributor to losses, which cost electricity utilities an estimated $96 billion per year worldwide (Bellero, 2017). We use the term "losses" to refer to transmission and distribution (T&D) losses, which comprise two major components. Technical losses, which are typically below 6%, are expected due to natural dissipation in the distribution system (Abdollahi et al., 2020). The second component, and this paper's main focus, is unbilled consumption.[4] High unbilled consumption is the primary reason why losses are three times greater in low and lower-middle income countries than in high-income countries (IEA/OECD, 2018).

Karachi Electric (KE), the distribution company serving Karachi, introduced ABCs in 2015 with the goal of making the electricity infrastructure more theft-resistant. This paper provides causal evidence on the impacts of this supply-side technology on the utility's financial measures and consumer outcomes, which are not obvious *ex ante*. Even with theft-resistant cables installed, consumers may use other channels to keep their consumption unbilled (e.g., manipulating meters), thereby offsetting the effects of the intervention.

Pakistan is a suitable setting for this study due to its high losses and unreliable elec-

graphically infeasible for many distribution companies. Utilities instead use aerial lines, which can be bare wires or covered conductors. ABCs are a commonly used type of covered conductor. Early ABC installations in high income countries were often justified on the grounds of safety, because ABCs reduce accidental human and animal contact, are less prone to puncture by trees, and are less likely to cause forest fires than bare wires (Murray, 1995; Oliveira et al., 1996; Li, Su and Shen, 2010). Those same physical properties that make ABCs less likely to be pierced by trees, also guard against illegal connections and therefore reduce non-technical losses.

[4]This is also referred to as non-technical losses.

tricity service. As of FY 2019-2020, Pakistan's distribution companies reported T&D losses between 9% and 39% (NEPRA, 2020). KE's average loss rate of 19.7% (NEPRA, 2020), hides considerable heterogeneity and very high losses within the utility's service territory. Furthermore, Pakistan is in South Asia, the region with the most power outages in the world (Zhang, 2018). To limit the financial burden associated with their low cost recovery, some distribution companies in the region ration electricity (Burgess et al., 2020).

To estimate the impacts of theft-resistant cables, we use differences in their installation across Karachi over time. The speed of KE's conversion process increased in 2018, when the utility began targeting feeder-lines with high and very high losses. Within a feeder-line, the installation would begin at one pole-mounted transformer (PMT or simply transformer from here onward), which typically serves a neighborhood of approximately 200 customers. The utility then employed a "ring fencing" strategy to minimize spillovers; once installation occurred at one transformer within a feeder-line, KE then converted the closest transformers to ensure coverage within a feeder-line.

Our identification strategy is based on the assumption that, conditional on fixed effects, the roll-out of theft-resistant cables is exogenous. Given that the utility's roll-out strategy depended on predetermined feeder-line characteristics, we control for feeder-line fixed effects and account for the time-invariant characteristics of these different areas (e.g., community culture, historical losses). Additionally, we control for time varying changes across KE's management offices (called integrated business centers, or IBCs) across the city (e.g., management changes, regional initiatives, budget allocations) with IBC-by-month fixed effects. Event-study models demonstrate the absence of pre-trends in our outcome measures. To address any potential bias from the two-way fixed effects model with staggered treatment timing (Goodman-Bacon, 2021), we employ recently developed robust estimators (Callaway and Sant'Anna, 2021; Sun and Abraham, 2021). Finally, we conduct a battery of robustness checks to alleviate potential additional concerns (e.g., spillover effects or contemporaneous policies targeting high-loss feeder-lines).

We use a unique combination of datasets, comprising utility data and our own household survey data. Utility data include information on the timing and location of cable conversion, as well as monthly distribution losses and revenue recovery for almost 1,900 feeder-lines over three years. Panel data on billing-related outcomes for approximately 3,000 residential utility customers enable us to investigate the mechanisms through which theft-resistant cables affect outcomes. Lastly, survey data that we collected in fall 2021 for these 3,000 customers permit us to better understand the effects on consumers.

Our analyses provide key insights on losses and the impacts of a supply-side technology designed to abate them. First, the conversion of bare wires to theft-resistant cables significantly and meaningfully reduced losses by 8.2 percentage points, from the baseline mean loss rate of 38.7%. These effects on losses persist for at least two years after installation, indicating that this was not just a short-run effect of removing illegal connections during the installation process (that individuals are able to reconnect). We interpret these effects as primarily arising due to reductions in unbilled consumption (i.e., theft), as additional analyses rule out technical losses as a significant channel driving the results. Specifically, we find no evidence of loss reduction in low loss feeders that underwent cable conversion only because they were located close to high loss feeder lines nor do we observe any additional negative effects of cable conversions on losses in feeders with characteristics that are indicative of higher technical losses (e.g., higher load). Moreover, engineering studies on theft-resistant cables from a similarly high loss context (Abdollahi et al., 2020) also support this interpretation that loss reductions came primarily via decreases in unbilled consumption.

We also find that bill payment significantly increased, but to a lesser and noisier extent (than losses) and this effect dissipates over time. This smaller effect on bill payments is not surprising. The cables prevent illegal connections, but do not provide additional mechanisms for enforcing bill payment.

The greater the intensity of cable conversion within a feeder-line, the larger the effects were on both financial measures (losses and bill payment). Furthermore, the technical intervention had the greatest impacts on unbilled consumption (bill payments) among the feeder-lines with the highest unbilled consumption (lowest bill payment) prior to the intervention. Cost-benefit analyses make evident that the cable conversion pays for itself through these reductions in losses.

Evidence indicates that these financial gains come via two primary channels. First, the number of formal residential utility customers significantly increased soon after conversion to theft-resistant cables, suggesting that previously informal consumers quickly learned that unbilled consumption was no longer feasible and switched to formal, billed connections. Second, among formal customers, conversions led to significant increases in monthly bills, both the number of units billed (kWh) and the monetary value. These results – in addition to reductions in indicators of theft and irregular billing and increases in the likelihood of bill payment – suggest that some formal customers previously used both formal and informal connections. Following conversion to theft-resistant cables, they shifted all consumption to their formal connection.

Shifting to the effects of theft-resistant cables on consumers, we show that after the reduction in utility losses, both the hours of load shedding and consumers' complaints to the utility decrease.[5] However, a more nuanced analysis indicates an increase in complaints related to utility billing errors. We compliment that causal evidence with correlational analyses that uses our cross-sectional survey data and sheds light as to how consumers might experience these effects. Consistent with the reduction in load shedding hours, cross-sectional comparisons of areas with and without the theft-resistant cables find significantly less load shedding in the former than the latter. These households also report owning more appliances, using their appliances for more hours per day on average, and incurring higher electricity expenditures. Lastly, and consistent with the increase

[5]The change in load shedding hours occurs because the utility's policy assigns load shedding according to losses. As we describe in detail later, higher loss feeders are allocated more hours of load shedding per day. So when a feeder has a decrease in losses, the hours of load shedding should fall, per utility policy.

in consumer billing complaints, analyses indicate that those in areas covered by the cables are more likely to believe that there are bill errors and less likely to believe that bills accurately reflect their electricity use.

This paper's main contributions are to the literature on the provision of services in developing countries. The study provides evidence on a path to mitigate the financial crises facing utilities in many developing countries through a technical intervention.[6] Although existing studies provide evidence on efforts to mitigate high subsidies and interventions to increase bill payment for water and electricity utilities in developing countries (e.g., through pricing reforms (McRae, 2015a; McRae and Meeks, 2016; Alberini, Bezhanishvili and Ščasný, 2022; Beyene et al., 2022*a*), pre-paid meters (Jack and Smith, 2020; Beyene et al., 2022*b*), and informational interventions (Szabó and Ujhelyi, 2015)), causal evidence on interventions to reduce unbilled consumption remains limited.

Moreover, the study fills a fundamental gap in the literature by estimating the effect of a technological intervention on losses. Our main result – that theft-resistant cables can reduce unbilled consumption – is generalizable to other developing country settings where theft is high and the utility has incentives to install the technology, regardless of the load shedding policies or other regulations.[7] Our supplementary result that this intervention leads to less load shedding and thus more power being supplied to treated areas might not hold more generally, as load shedding policies may differ elsewhere. However, we note that as any utility's financial losses decrease there can be dynamic effects enabling utilities to purchase more electricity and increase overall supply.

Second, in addition to the utility-side impacts, this paper provides insights into the nuanced effects of this technical intervention on consumers. Given the difficulty in both accessing administrative data and being able to match it with in-depth survey data, stud-

[6] Given that electricity utilities are commonly publicly owned and operated (or if privately owned, the government is often a majority stakeholder), we also see this adding to a broader literature on public sector financing in developing countries (Pomeranz, 2015; Kumler, Verhoogen and Frías, 2020; Khan, Khwaja and Olken, 2016; Carrillo, Pomeranz and Singhal, 2017).

[7] The extent to which they have the incentive to reduce theft differs across utilities. Not all utilities have incentives that are aligned with installing the theft-resistant cables.

ies analyzing utility interventions from multiple angles remains relatively rare. Combining utility records – on both utility and consumer outcomes – with the in-depth consumer survey permits a more comprehensive set of analyses.

Finally, these results show that a purely supply-side technical upgrade offers a partial way to shift the electricity sector from a bad equilibrium with high theft, low payments, and poor service delivery (Burgess et al., 2020) to a better equilibrium. However, there are reasons for caution due to consumer-side issues. Although we find improvements in both utility finances and service delivery following the technology upgrade, we find no significant differences in customers' trust in the utility. In fact, customers in areas with theft-resistant cables are more likely to believe that the utility makes billing errors. Further exploratory analyses indicate that (presumptive) newly formal customers consume fewer units of electricity than incumbent customers, with a substantial portion below the cutoff for the bottom tier of the increasing block price. This suggests that the newly formal customers are poorer than the incumbents and that the tariff may not be functioning as well as intended. Together, these findings suggest that moving to an equilibrium with greater willingness to pay may require complementary demand-side reforms targeting bill payment.

The paper proceeds as follows. Section 2 provides background information on electricity distribution in Karachi. Section 3 provides a framework for conceptualizing the impacts of theft-resistant cables. Section 4 details the utility data and our household survey. Section 5 describes the empirical models underpinning our estimations. Section 6 presents results on the intervention's impacts on utility-level outcomes. Section 7 reports estimated effects of the intervention on consumers. Section 8 concludes.

2 Background on Electricity in Pakistan

2.1 Electricity in Pakistan: Overarching Sector Issues

Pakistan's power sector has long been beset with challenges, frustrating the goals of providing affordable and reliable electricity (Younas and Ali, 2021). The power sector has undergone major reforms since the early 1990s and is now regulated by the National Electric Power Regulatory Authority (NEPRA).[8] Yet the sector continues to struggle with frequent outages and financial challenges, particularly high incidences of unbilled consumption and non-payment of bills. Additionally, tariffs historically were set substantially below the cost of supplying electricity (Munasinghe, 1984). Together, these challenges mean that the distribution companies achieve full cost recovery on only a fraction of the units supplied and are trapped in a sub-optimal equilibrium with overburdened infrastructure, high losses, intermittent load shedding, and growing circular debt.[9]

Pakistan's high-cost and largely non-renewable generation mix has economic and environmental consequences. From an environmental perspective, Pakistan's generation is highly polluting. As of June 2021, the share of the installed capacity due to non-renewable sources stood at close to 70%.[10] From the financial perspective, high losses make it difficult to fund generation, as the majority of fossil fuels used for the country's electricity generation are imported. In Appendix A1, we detail how the utilities in Pakistan are financially constrained in their ability to purchase fossil fuels for generation and how that necessitates load shedding.

[8] Bacon (2019) discusses the various power sector reform initiatives in Pakistan.

[9] Circular debt refers to chain of receivables that accumulates along the electricity supply chain when distribution companies are unable to pay fully for the electricity purchased from generation companies.

[10] Renewable energy (hydroelectricity, wind, solar) in the generation mix was around 30% with 12,062 MW, while the share of non-renewable thermal power plants (gas, oil, coal, and nuclear) was around 70% with 27,711 MW (NEPRA, 2021*b*). During fiscal year 2020-21, the share of gas, regasified liquefied natural gas, residual furnace oil (RFO), coal, and high-speed diesel generation in total thermal generation stood at 20.20%, 35.82%, 11.96%, 31.59%, and 0.45%, respectively. The heavy reliance on thermal generation would clearly be contributing to the environmental pollution due to the release of CO_2 from the burning of fossil fuel and contamination of waterways due to the waste water discharged by power plants (NEPRA, 2021*b*).

2.2 Electricity Distribution in Karachi

The context of this research is the electricity distribution network in Karachi, the largest and most densely populated city in Pakistan. Karachi Electric, which is a vertically integrated and privately-owned power utility, is the sole provider of electricity services in Karachi.[11] The utility has a distribution network spanning an area of 6,500 square kilometers, covering 2.5 million residential, commercial, industrial, and agricultural consumers.

The company's distribution network is divided into areas covered by local offices (IBCs), which handle electricity distribution, billing, and collection in their respective territories. Of the utility's 30 IBCs, 12 are categorized as high loss with average unbilled consumption exceeding 30% of the total units sent out. Bill payment rates are below 80% in these areas, which have a large fraction of lower-income customers residing in semi-formal and informal settlements. Appendix A1 describes how Karachi Electric allocates load shedding according to average feeder line losses.

Kundas, informal and unauthorized connections to the main electricity distribution cables, are a common sight in many Karachi neighborhoods.[12] The use of kundas on bare wires mean that the electricity infrastructure is nonexcludable. KE is well aware that kundas are the main source of unbilled consumption. Historically, KE field staff continuously monitored high loss areas to detect and disconnect kundas and fine perpetrators.[13] However, with a distribution network comprised of bare wires, there is little deterring people from re-connecting a kunda immediately after it is disconnected. In many communities, households access electricity through kundas that are put in place at night and removed

[11] KE is a publicly listed company with the Government of Pakistan holding 24% ownership and the remaining shares owned by a consortium of private investors. Although KE was privatized as of 2005, the other ten distribution companies operating in Pakistan have not been (Bacon, 2019).

[12] The local distribution infrastructure typically consists of a sub-station (receiving electricity from the grid station), a 11 Kv feeder-line carrying electricity from the sub-station to a transformer, and low-tension cables (220-440V) carrying electricity from the transformer to the customers. A kunda is usually hooked on the low-tension cables originating from the transformer.

[13] Kunda removal drives are regularly conducted by KE across all high loss areas. Areas with high kunda usage are identified by meter inspection officers during their field visits. These officers identify and collect visual evidence on kundas. The IBC staff analyses this evidence and mobilizes removal teams to carry out kunda removal.

early in the morning to avoid detection. This is particularly common in the hotter seasons, when households are more likely to use electricity for cooling services.

When a house or business connects via a kunda, it is not necessarily at a zero cost. In some neighborhoods, informal groups facilitate kunda connections; the customer pays an upfront cost for the initial kunda and then a monthly fee for continued use. These informal groups are most common in the neighborhoods in which KE historically did not have formal service provision. KE has extended the distribution network to serve these neighborhoods, but a culture of informal connections persists.

The process to get a formal grid connection through any of Pakistan's distribution companies, including Karachi Electric, is determined by the regulatory agency (NEPRA, 2021*a*). The connection charges are typically comprised of the store cost for materials (meter, etc.) and installation charges, which are 8% of material costs. Material costs vary depending on the connected load and the cable length required to reach the new customer's premises. In total, residential customer connections cost at least 100 USD.[14] According to KE, this process can take approximately three months or more (from the customer's application submission to the utility completing the connection) and depends on a number of factors (e.g., whether there is load available at the transformer/feeder, availability of materials, how quickly the applicants pays the security deposit for connection fees).

2.3 Bare Wires to Aerial Bundled Cables

Efforts to minimize electricity tariffs in low and lower-middle income countries mean that the quality of infrastructure construction and service provision often diverges from that which is found in middle and high income settings. In high income countries, low voltage electricity distribution lines are often either buried underground or are comprised of covered conductors, such as aerial bundled cables (ABCs). Distribution companies in

[14]This estimate is based on our communication with KE and is for a 15-20 kW connection costing 30,000 PKR. Connection costs increase for higher loads.

lower income countries have historically installed the least costly option: bare wires. We summarize distribution technologies below and provide more detail in Appendix A2.

2.3.1 Distribution System Technologies

Bare distribution lines are prone to storm damage (e.g., falling branches may puncture them) and therefore outages, safety challenges (e.g., electrical shock, fire risk, accidental contact with people and animals), as well as environmental concerns (i.e., extensive tree clearance required to prevent forest fires), and electricity theft via illegal connections (La Salvia, 2006; Southern California Edison, 2018). Yet, bare wires are still common in LICs and LMICs (Agarwal, Mukherjee and Barna, 2013), as low tariffs, low bill payment, and high unbilled consumption often limit distribution companies' revenue and therefore their ability to cover such infrastructure costs (International Energy Agency, 2020).

ABCs are not a new technology, but their installation primarily for their theft-resistant properties is relatively recent. Early installations are documented in high income countries during the second half of the 20th century. At that time, ABCs were considered revolutionary and hailed as "the biggest step forward in overhead distribution line practice in 50 years" (Williamson et al., 1989). Installing ABCs is cheaper than burying distribution lines underground, but they cost an estimated 1.4 times more than bare wires.[15] Since the 1980s, ABCs have become ubiquitous in many high income countries (La Salvia, 2006), with installations justified by their better personal safety (e.g., reducing accidental human and animal injury) and greater resistance to external abrasion and tree puncture (Murray, 1995; Oliveira et al., 1996; Li, Su and Shen, 2010).

With financial problems pervading the electricity sector in many developing countries, reducing losses is increasingly prioritized and recent literature argues that replacing basic wires with ABCs is considered a "practical and effective" solution to reducing non-

[15] Analyses comparing the costs of replacing existing distribution lines with either new bare conductors, new covered conductors such as ABCs, or relocating the conductors underground, the costs were estimated to be 0.3, 0.43, and 3 million USD per mile, respectively (Southern California Edison, 2018).

technical losses (Abdollahi et al., 2020). Due to their intertwined cable design, the technology makes puncturing lines to connect kundas difficult. In the past 15 years, ABCs have been installed with the specific purpose of reducing theft, and unbilled consumption more broadly, by utilities in countries such as Brazil, India, Iran, Mexico (La Salvia, 2006; Agarwal, Mukherjee and Barna, 2013; Abdollahi et al., 2020).

Engineering simulation studies indicate the ABCs are highly effective in eliminating non-technical electricity losses. These studies indicate that ABCs can also reduce naturally-occurring technical losses. However, given technical losses represent a small fraction of T&D loss reduction in high loss settings, any reduction in losses due to ABCs in settings such as ours are expected to be predominantly driven by reductions in unbilled consumption. For Karachi Electric, the primary goal of ABC conversions was to reduce theft (as opposed to technical losses), as we discuss in greater detail below.

2.3.2 ABCs in Karachi, Pakistan

In an effort to decrease unbilled consumption, KE launched an initiative to convert bare wires to ABCs, specifically for their theft-resistant properties. Conversion began in 2015 as a pilot intervention in a small number of transformers and in 2018 it was expanded to specifically target the high loss IBCs in Karachi. To ensure the conversion did not divert KE's labor from on-going regular operations, the utility outsourced the conversion process. Figure 1 shows the incremental and cumulative installation of theft-resistant cables between 2014 and 2021, in terms of the number of transformers on which the cables were installed. Appendix maps (Figure B1) depict an example of the installation spatially across one IBC over time.

Two factors affected the roll-out of theft-resistant cables in Karachi. First, the roll-out was determined by KE's business strategy. Initially, budgets were set by the utility's strategy department and included targets for the number of transformers to be converted. Since the majority of the cable installation work was outsourced, these budgets were set according to the execution capacity of outsourced manpower. After 2018, KE adopted the policy of targeting transformers in feeder-line areas designated as high-loss and very high-loss based on their historical records. Second, the roll-out of the cables was subject to resource constraints. KE prioritized installation to meet targets, following the ring-fencing strategy described earlier.

ABCs were primarily intended to curb unbilled consumption, as opposed to making the distribution system more robust to weather related damages. For example, the areas located close to the coast, which are most susceptible to storms and weather damage, have very low cable conversion rates as these areas were and continue to be designated as low loss.[16] Furthermore, KE's internal reports show that ABCs were not viewed as a means to reduce technical losses.

3 Conceptual Framework

In this section, we conceptualize how the installation of theft-resistant cables could benefit producers (the distribution company), as well as potentially affect customers.

The electricity utility (in this case, KE) distributes electricity to its formal customers. The utility charges its customer a single fixed per kWh price, P_f, as set by the regulator.[17] The customer's consumption (kWh) is measured via a meter, based upon which the company bills the customer. As presented in Burgess et al. (2020), there are multiple reasons, including unbilled consumption, as to why the the utility collects, on average, an amount per kWh that is lower than the price set by the regulator, P_f. Following Burgess et al. (2020), we refer to this as an effective price, P_e. The incidence of unbilled consumption varies across feeder-lines. Given the high incidence of unbilled consumption, we know that $P_e \ll P_f$ and this contributes to the utility's budgetary constraints.

[16] By the end of our sample period 56% of all transformers in high loss IBCs were converted to ABCs. The corresponding figure is 0.2% for the rest of Karachi.

[17] We assume a single per unit price for simplicity, without loss of generality.

The budget constraints affect electricity supply and necessitate electricity rationing. To do so, KE categorizes feeder-lines as high, medium, or low loss, with high loss areas defined as those where KE has the lowest levels of cost recovery. KE then varies the amount of load shedding across high and medium loss areas, with feeder-lines with higher losses having greater rationing (lower quantity supplied to the feeder-line, with more hours of load shedding). Feeder-lines designated as low loss have no load shedding.

Theft-resistant cables have the potential to make electricity infrastructure excludable, by limiting the feasibility of kundas and thereby shifting their users to formal connections. If they do prevent kundas, then we expect KE to be better off, as this would decrease the difference, on average, between P_f and P_e. If kundas are prevented, we expect to see an increase in the number of formal consumers and a reduction in unbilled consumption.

Although the stated objective of this intervention – and the main focus of our study – is improvement in the utility's finances, the intervention will also affect the utility's customers. There are multiple ways that theft-resistant cables may affect consumers. First, an increase in the effective price of electricity would intuitively make customers worse off; if their consumption of electricity services remains constant, their electricity expenditures would increase, potentially affecting non-electricity expenditures. However, KE's load shedding policy may result in a reduction of rationing as losses fall. This would benefit customers by allowing them to buy appliances and consume more of their services.[18] Further, a reduction in the use of kundas may improve the quality of electricity services (e.g. lower fluctuations and outages due to damage caused by kundas), an effect that would not be measured by simple changes in surplus. We therefore leverage both KE provided data and data we collected from a cross section of the utility's consumers to determine the direction of these effects.

[18] In Appendix Section E we present a simple model of consumer surplus and report results from exploratory analysis of the effects of the theft-resistant cables on consumer surplus. While acknowledging concerns about the validity of estimating surplus as a relevant welfare measure in the presence of theft, the exercise helps highlight not only the restrictive assumptions required for such analysis, but also the potential for both positive and negative effects of the change on consumers.

4 Data

The analyses utilize data from two sources. First, through a non-disclosure agreement, the utility shared extensive data at the feeder-line, transformer, and consumer levels. In addition, we collected survey data for a sample of utility customers.

4.1 Utility Feeder-line and Cable Conversion Data

We assembled a comprehensive and unique dataset including estimates of feeder-level losses, percentage of billed amount paid, utility claims, consumer complaints, consumer numbers and date of cable conversions of transformers from KE.[19] Further details of the utility datasets are as follows:

Utility Financial Indicators. There are two variables that are primary indicators of utility financial health: *losses* and *revenue recovery*, respectively. The data on feeder-level monthly losses and revenue recovery cover all feeder-lines in Karachi from January 2018 to October 2020.

Losses are measured as the difference between units sent out and units billed and then divided by units sent out. Losses are therefore the proportion of the electricity sent out that is not billed. Note that this is in essence an estimate of total T&D losses, as there is no way to distinguish between unbilled consumption and technical losses.

Revenue recovery is defined as the ratio of net credit to billing. In other words, it is proportion of billed electricity consumption that is actually paid.

Consumer Complaints. We collect data on consumer complaints, which are tickets submitted by KE customers regarding issues such as billing, technical problems, and service concerns for the contract account, from January 2018 to June 2021. For each complaint, we observe information on the topic, timing, and the corresponding feeder-line. The data are then aggregated to the feeder level on a monthly basis.

[19] These outcomes obtained from utility's administrative records are measured at the feeder-line level. Transformer level data on these outcomes are not available during the period of our study.

Consumer Number. For each feeder-line in Karachi, we collect monthly data on the number of active consumers in each category, including agricultural, bulk, commercial, industry, and residential consumers, between January 2018 and March 2021.

Theft-Resistant Cable Installation. KE provided the dates when cables were upgraded in each transformer. We observe the installation record through January 2021. To match these data with feeder-level monthly variables, we create two measures for cable installation. First, we define a binary indicator for whether a feeder-line has at least one transformer where cables were upgraded. Second, we calculate the ratio of transformers with theft-resistant cables installed relative to the total number of transformers in a feeder-line.

Contemporaneous Initiatives. We collect data from KE on the other utility initiatives that had the potential to affect the financial outcomes that we study (losses and revenue recovery) and that overlapped in timing with the study period. These data are further detailed in Section 6.1.2, where we explain the robustness checks.

4.1.1 Feeder Line Summary Statistics

Our final monthly dataset covers 1,888 feeder lines in Karachi. We calculate baseline summary statistics for sub-groups of feeders (Appendix Table C1). Of these, 1,509 feeder lines are not treated with the theft-resistant cables before the end of our study period ("never ABC"), whereas 194 feeders are treated during our study period ("ABC treated").[20] We present the means and standard deviations of baseline characteristics for both groups. We can further decompose the treated group into those feeders treated earlier ("early ABCs") and those treated later ("late ABCs") in the study period. We compare the early versus late treated feeder lines on a number of baseline characteristics, which is helpful for both our empirical strategy (described in Section 5) and for interpreting the estimated effects.

We can also compare the treated feeders with the never treated feeders. As expected,

[20] In order to capture baseline characteristics for the feeder lines that are treated in our study period, we omit from these calculations feeders that were treated during or before January 2018.

given treatment was determined using certain baseline characteristics (i.e., losses), the feeder lines without theft-resistant cables installed are statistically significantly different from the treated feeders in multiple ways.

4.2 Utility Residential Consumer Data

For a subset of residential customers, which are also the households surveyed as described in the following sub-section, we obtain the corresponding consumer-level data on billing and payment behaviors from KE. The sample covers the period between June 2018 and August 2021. In the data, we observe information on monthly billed units of electricity (both the kWh and the monetary amount), the amount and date of bill payment, total monetary amount due to KE, and the billing category mode (BCM).[21] These data allow us to check whether a customer paid their bill in a billing cycle or not.

4.3 Household Survey Data

In October and November 2021, we surveyed approximately 3,000 residential customers across 150 transformers. We randomly selected households from the utility's roster of consumers in a multiple-step process. We restrict the sampling to high-loss feeders within eight of KE's regional offices (IBCs). Within these feeder-lines, we restrict to transformers with a minimum of 80 customers and a maximum of 500 customers, to both ensure we have sufficient households to allow for replacement and to avoid outlier transformers with particularly large numbers of customers. This leaves more than 1,500 transformers from which to select. We randomly select 150 transformers, ensuring that transformers both with and without theft-resistant cables are represented in the list. Selected trans-

[21] The BCM variable allows us to observe whether billing occurred in a normal manner or whether there are irregular bills. If a consumer has a normal BCM, it means that the meter functioned properly and there were no errors in billing. There will be irregular bills if the meter stops working or becomes faulty, or if there are other errors in recording units or calculating bills. Irregular bills also occur when there is a case of theft or kunda detection by KE. According to the BCM classifications, we are able to identify customers with irregular bills or those alleged by the utility to have engaged in theft in a month.

formers serve, on average, 202 residential customers each. Within transformers, we limit our sample to residential customers with active accounts and then randomly select 20 customers per transformer to survey.

The questionnaire collects information on basic household characteristics, demographics, and other outcomes related to electricity consumption. We collect data on appliance ownership and use, as well as household expenditures (both electricity and non-electricity related). Questions also cover household perceptions about the level of theft and payment practices in their neighborhood, as well as respondents' beliefs about the utility, electricity service quality (both load shedding and voltage fluctuations), tariffs, billing, and payment practices.

From these survey data, we learn about the households in this setting and their general demographic information (Appendix Table C2). Households, on average, consist of seven individuals: four adults and three children. The majority of those surveyed (79%) are owners of the home, rather than renters. The houses have three rooms, with approximately three-fourths are pucca (i.e. constructed of bricks and cement) and one-fourth made of more rudimentary and temporary materials (katcha). Only 5% of surveyed households report owning land.

In terms of their electricity-related characteristics (Appendix Table C3), the surveyed households report summer and winter monthly electricity bills of 5,635 Pakistani rupees (PKR) and 3,886 PKR, respectively. Summer is not only the time of peak electricity bills; summer also has greater outages or load shedding (7.6 hours per day) than winter (5.6 hours per day). These households own approximately seven appliances, on average, which typically include water pumps and refrigerators. Almost no households in the sample report owning an air conditioner.

5 Empirical Strategy

5.1 Losses and Bill Payment

To estimate the impact of conversion to theft-resistant cables, our research design leverages differences over time and across Karachi in the cable conversion process. The adoption of theft-resistant cables follows a staggered process, the timing of which mainly depends on KE's business strategy. Since the roll-out of the cables creates variations across feeder-lines and over time, we employ a staggered DID approach to identify the causal effect of the conversion on feeder-level losses and bill payment.

For feeder-line i of IBC region j in month t, we estimate the following regression model throughout our main analysis:

$$y_{ijt} = \beta \text{ABC}_{it} + \alpha_i + \delta_{jt} + \varepsilon_{ijt}. \tag{1}$$

The outcome variable includes losses and bill payment (measured using variables *losses* and *revenue recovery*, both in percentage points). The variable of key interest, ABC_{it}, is a binary indicator for whether a feeder-line i already had at least one transformer with theft-resistant cables installed in month t.

We add a rich set of fixed effects to control for unobservable determinants. We include a feeder fixed effect α_i to capture feeder-level time-invariant unobservable factors that may affect both the outcome and cable conversion, such as the baseline feeder-line categories. We also control for IBC-specific time fixed effects δ_{jt} to account for regional policy shocks or potentially differential time trends across IBCs, such as changes in IBC management, allocation of budgets, regional initiatives, or revision of targets. The standard errors are clustered at the feeder-line level.

In an alternative model specification, we explore the intensity impact of the theft-resistant cables by replacing the ABC indicator with the ABC ratio, which, as previously defined, is the ratio of the transformers within a feeder-line that have been converted to theft-resistant cables.

We adopt the standard two-way fixed effects model as the main specification for our primary outcome variable (losses). We argue this is appropriate because, for multiple reasons, we do not expect the treatment effects on losses to vary by cohort – a primary concern when using the two way fixed effects model. First, our feeder line summary statistics (Appendix Table C1) showed no baseline differences in losses between the "early" and "late" treated cohorts. Second, it is unlikely that the later treated feeder lines were changing their loss-related behaviors in anticipation of treatment (e.g. customers would not give up their kundas any earlier than necessary). Third, our event study estimates for losses can capture the evolution of treatment effect over time. Moreover, we can present the robustness of our loss-related results to alternative estimators used in staggered difference-in-differences models proposed by Callaway and Sant'Anna (2021) and Sun and Abraham (2021).

5.2 Validity of Identification Strategy

Our identification strategy takes advantage of variations in outcome measures specific to feeder-lines with theft-resistant cables installed relative to those feeder-lines without cables installed, and in periods before and after the conversion. Based on KE's business strategy, the roll-out of the cable conversion depends on predetermined feeder-line characteristics in terms of loss categories, resource constraints, and local resistance. By including our fixed effects, the model can account for a range of omitted variables that could otherwise bias the estimates. After adjustment for these fixed effects, the roll-out time is conditionally independent of unobservable factors that may affect unbilled consumption and bill payment. We discuss the identifying assumptions and potential threats in the following paragraphs and provide more details on efforts to address these concerns in Section 6.1.2.

Parallel Trends Assumption. The DID approach requires parallel trends in the outcome variable between the treatment group and the control group in the absence of the cable conversion. To provide evidence that the assumption holds prior to treatment, we estimate the dynamics of unbilled consumption and bill payment using the event-study framework. Specifically, we include leads and lags of the cable conversion indicator in the baseline regression to trace out the month-by-month effects:

$$Y_{ijt} = \sum_{\substack{-15 \leq k \leq 21 \\ k \neq -1}} \beta_k \mathbb{1}[t - \tau_i = k] + \alpha_i + \delta_{jt} + \varepsilon_{ijt}. \tag{2}$$

The dummy variables, $\mathbb{1}[t - \tau_i = k]$, jointly represent the theft-resistant cable conversion events. Specifically, τ_i denotes the first month when feeder-line i started having theft-resistant cables at its transformers, and k measures the gap between the current month and the initial deployment month τ_j. A negative k represents the pre-conversion month while a positive k represents the post-conversion month. Controlling for leads allows us to examine the pre-treatment effects as a test for parallel trends. Controlling for lags enables us to trace the effects in the periods after the initial conversion. Note that the dummy for $k = -1$ is omitted from Equation (2) so that the estimated effects are relative to one month prior to the conversion. If the results show that the estimated coefficients for the leads of the theft-resistant cable conversion dummy are small in magnitude and statistically indistinguishable from zero, then there is no evidence of meaningfully differential trends in losses and bill payment in advance of the conversion. This would provide support for the parallel trends assumption.

Addressing Feeder-Level Confounding Factors. With the feeder-line and IBC-by-year fixed effects, we are able to account for a rich set of time-invariant feeder-level characteristics or IBC-specific shocks that might confound identification. The remaining concern stems from time-varying feeder-level changes. We address this issue as follows. First, we include additional fixed effects, such as IBC-by-loss-category-by-month or feeder-by-calendar-month fixed effects, to capture differential seasonal patterns or loss mitigation efforts across feeder-lines. Second, to address the concern that theft-resistant cable installation might be affected by the utility's anticipation of feeder-level changes, we conduct robustness checks focusing on feeder-lines that are followers of the initial cable conversions according to KE's "ring-fencing" strategy and therefore their conversion schedules are likely to be exogenous. We note that we are unable to cleanly separate the target transformers from the "ring-fenced" transformers as this information is not available in the roll-out schedule.[22] However, we perform the robustness check discussed here on the basis of conversion timing. Finally, we also obtain data on contemporaneous initiatives that were launched by the utility at some point overlapping with our study period and that might either affect theft or bill payments, and check the robustness of our results after accounting for these initiatives.

Stable Unit Treatment Value Assumption (SUTVA). Another identifying assumption is that there are no spillover effects on feeder-lines in our control group. Specifically in our setting, it means that the cable conversion of one feeder-line does not affect other feeder-lines that have not yet been converted. Since the cable conversion work was conducted by an outside vendor, we are able to exclude the possibility that the utility's labor force was diverted from untreated areas. Given the utility employs load shedding, one might expect that as losses and thus load shedding decline for the converted feeder lines, untreated feeder lines experience more load shedding. However, according to the utility's official policy, load shedding in Karachi is assigned at the feeder-line level and determined based on the individual feeder-line's loss levels (Appendix A1). Furthermore, as part of its annual load planning exercise, the utility accounted for potential changes in demand following the cable conversions, and adjusted its supply accordingly (through generation and purchases). Lastly, we note that the treated area of study in this paper is

[22] Unfortunately, we are unable to leverage the "ring fencing" strategy for our main specification, as we do not know exactly which transformers were targeted versus "ring fenced." Additionally, as our outcomes are at the feeder-line level, aggregating the "ring fencing" strategy to the feeder-line level would potentially create measurement errors (i.e., one feeder line could have both targeted and "ring fenced" transformers).

relatively small compared to the entire distribution network (194 feeder lines out of the total 1,888 feeders). For these reasons, load shedding in untreated areas is unlikely to be affected systematically by the treatment and, if it is, we expect it to be quite small.

Lastly, one may be concerned that households located in converted areas instead connect their kundas to nearby untreated feeder-lines. This concern is alleviated due to KE's "ring fencing" strategy – once the theft-resistant cable installation starts at a transformer, the company will convert other transformers in neighboring regions. To further address this issue, we also conduct robustness checks by excluding feeder-line areas that are very close to each other from our sample.

5.3 Consumer Bill Analyses

To complement the analysis of the utility-level impacts, we investigate the consumer-level response to theft-resistant cables using panel data on residential customers' billing-related outcomes. We conduct both event studies and DID regression analyses of the cables' impacts on residential customers. For residential consumer i served by transformer j in month t, we estimate the following regression model:

$$y_{ijt} = \beta \text{ABC}_{jt} + \alpha_i + \delta_t + \gamma_{j\tau(t)} + \varepsilon_{ijt}. \tag{3}$$

The outcome variables include different consumer-level measures on billed electricity consumption, payment behavior, and theft. The variable of key interest, ABC_{jt}, is a binary indicator for whether transformer j already has theft-resistant cables installed in month t. We add consumer fixed effects (α_i), month fixed effects δ_t, and transformer by month-of-year fixed effects $\gamma_{j\tau(t)}$ to capture unobservable factors. Standard errors are clustered at the transformer level.

6 Effects of Theft-Resistant Cables on the Utility

In this section, we present results from our baseline model that suggest that this technical intervention resulted in a reduction in losses and an increase in bill payments. To understand the channels through which these impacts occurred, we also investigate whether the cable installation affected technical losses, the number of utility customers, or customer bill payment behaviors. The section ends with cost-benefit analyses to illustrate how quickly the investment pays for itself.

6.1 Losses and Bill Payment

6.1.1 Main Results

We investigate the effects of the cable installation through both event studies and regression analyses. The event studies in Figure 2 estimate the difference between the feeders that were "treated" via installation of theft-resistant cables on at least one transformer and those that were not (the "untreated"), controlling for both IBC-by-month and feeder fixed effects.

These event studies provide two key results. First, they show that the estimated coefficients for the leads of the theft-resistant cable conversion dummy are small in magnitude and statistically indistinguishable from zero. Hence, there is no evidence of meaningfully differential trends in losses and bill payment in advance of the conversion, which provides support for the parallel trends assumption. Second, these results illustrate a significant negative effect on losses and a positive effect on bill payment from the theft-resistant cable installation. These effects persist for the duration of the study period. For losses we observe that the effect fully materializes within six months likely reflecting the time to fully convert all transformers within a feeder line. Revenue recovery impacts are noisier and dissipate towards the end of the sample period. We explore this further in the robustness checks (Section 6.1.2).

We further investigate this relationship through DID analysis, as depicted in Equation 1. Results showing the estimated impact of theft-resistant cables – using the indicator for cable installation on at least one transformer within a feeder-line – on losses are in Table 1, Panel A. Results from regressions using our other measure of treatment – the intensity of cable installation within a feeder – are presented in Panel B of Table 1. These analyses are performed using both monthly and quarterly losses and revenue recovery data as outcome measures. All regressions include feeder fixed effects and some form of IBC-time fixed effect, depending on whether the analyses are using monthly or quarterly data.[23]

The results in both panels tell a consistent story. Theft-resistant cable installation, whether measured as a binary indicator or as a treatment intensity, led to significant reductions in losses and increases in bill recovery. In Panel A, the estimates in columns 1 and 3 suggest that losses decreased by 6.2 to 8.2 percentage points in feeders with theft-resistant cables. This reduction can be compared to the baseline mean loss rate in the treated feeders, which was 38.7% (Appendix Table C1, column 2).[24] Similarly, the estimates in columns 2 and 4 suggest that bill payment was improved by 5 to 5.2 percentage points, which is an increase from the 65% baseline average revenue recovery in these feeders. Panel B provides evidence that fully replacing all bare wires within a feeder-line with theft-resistant cables leads to even larger improvements in losses and bill payment. These results are also consistent with robustness checks in which we omit the first six months after a feeder line is converted and find estimated effects that are larger in magnitude than the main estimates (Appendix Table C7, Panel E).[25]

Additionally, we investigate whether the theft-resistant cables have heterogeneous effects, depending on the severity of the baseline losses and bill payment problems. We

[23] The results are robust to using alternative clustering approaches as shown in Table C4.

[24] We note that the estimated effects are identified off of the conversion of high loss feeders and therefore we should not expect the same effects if the same technology were installed in low loss feeders.

[25] Supplemental evidence, however, also indicates some non-linearities in the effect of the cable installation intensity. Specifically, we find diminishing returns on theft-resistant cables for bill recovery (Appendix Table C5).

classify the initial losses or bill payment rates (the monthly average losses and revenue recovery rate variables over January 2018 and June 2018) of the feeder-line into three categories by tertile: low, medium, and high. The ABC indicator is then interacted with binary indicators for those categories. We find that losses decreased more in the feeders that had higher levels of losses at baseline (Appendix Table C6). Similarly, bill payment increased more among the feeders with medium and low levels of baseline payments.

6.1.2 Robustness Checks

The results in Table 1 are robust to a number of checks, which are presented in the Appendix (Tables C7, C8, C9, C10, and C11) and summarized here.

"Ring-Fencing" and the Roll-out of ABC Conversion. We leverage the utility company's "ring-fencing" strategy to address the concern that the cable roll-out is correlated with time-varying feeder-line characteristics, such as anticipated reduction in theft or bill payments. As we previously explained, KE adopted the "ring fencing" strategy – once theft-resistant cable conversion starts, the company tries to cover neighboring regions – to prevent negative spillovers. One might worry about the endogeneity of theft-resistant cable conversion for the feeder-lines that started this process earlier. Their neighboring feeder-lines, however, are likely to be converted due to the "ring-fencing" strategy and therefore the conversion schedule can be considered exogenous. With that in mind, we conduct robustness checks by restricting our sample only to the followers of theft-resistant cable conversion (i.e., feeder-lines that did not have one of these "first converted" transformers). Specifically, we first create a 1km buffer zone around each feeder-line area. Next, for all the nearby feeder-lines that overlap with this buffer zone, we identify the earliest cable conversion date among them. Then, we drop the feeder-line areas if they are among the earliest to have the cables installed. This process is repeated across all feeder-line areas and we end up having only the followers of theft-resistant cable conversion in our sample. With this restricted sample, we re-estimate our baseline model. In addition, we also conduct more robustness checks by dropping the high-loss feeder-lines as well since they are more likely to be strategically targeted by the utility company during the conversion process. Our conclusions still hold (Panel A of Appendix Table C7).

Addressing Potential Spillovers. There are several types of potential spillovers, which we address here. First, if there are changes in load shedding in response to the theft-resistant cables installed, those changes must not affect untreated feeder-lines. In Karachi, load shedding is assigned at the feeder-line level based on the unbilled consumption and bill payment rates at that feeder-line. The algorithm used by the utility to allocate load shedding is depicted in Appendix A1. As Appendix Table A1 shows, low loss feeders are assigned 0 hours of load shedding per day. Hours of load shedding per day are positive and increasing for medium (3 hours), high (6 hours), and very high (7.5) loss feeders. These load shedding allocations are assigned not due to generation capacity constraints (as described in Appendix A1, the generators are operating at below capacity), but due to the costs of purchasing fuel for generation relative to the costs covered by customers' payments. So if one feeder has an increase or decrease in load shedding, that does not affect load shedding in another feeder line. This process by which Karachi Electric assigns load shedding at the feeder-line level and the fact that our analyses are using feeder-line level data also mitigate concerns regarding this potential SUTVA violation. In summary, although we cannot say that there are absolutely no spillovers of this kind in our study, we argue that any such spillover is arguably sufficiently small that it is inconsequential to our findings.

Second, the process of installing cables on some feeder-lines must not divert resources away from other feeder-lines, thereby affecting their outcomes. Given the magnitude of this task of replacing bare wires with the theft-resistant cables, the utility outsourced the vast majority of this work. With this work conducted by an outside vendor, the utility's labor resources were not diverted from untreated feeder-lines.

Third, theft must not spill over into untreated feeders by households located in neighboring areas with treated feeder-lines. In other words, households that can no longer pilfer from their closest feeder-line due to theft-resistant cable installation must not connect a kunda to a nearby feeder-line without such cables installed. This is mostly likely to occur in feeder-lines that are very close to each other. The concern on spatial spillovers can be mitigated by KE's adoption of the "ring-fencing" strategy when doing the conversion. To further address this issue, we re-estimate the baseline model excluding from our sample feeder-lines that are very close to each other. Specifically, we identify the center point of each feeder-line area by averaging the GPS coordinates of its transformers, and calculate the distance between each pair of feeder-line areas. We then re-estimate the baseline model by dropping the feeder-lines that have at least one nearby feeder-line within a 100 m, 300 m, or 500 m buffer zone. Results are in the appendix (Appendix Table C7 Panel B). Additionally, we control for the theft-resistant cable status of neighboring feeder-lines, by adding an indicator for whether there are conversions at transformers from other feeder-lines located within 100 m, 300 m, or 500 m distances (Appendix Table C7 Panel C). Both approaches yield similar results and alleviate concerns regarding such spillovers.

Heterogeneity-Robust DID Estimator. Recent literature shows the potential estimation bias of the two-way fixed effects estimator with varied treatment timing (De Chaisemartin and d'Haultfoeuille, 2020; Goodman-Bacon, 2021; Callaway and Sant'Anna, 2021; Sun and Abraham, 2021). Under a setting with staggered treatment timing and heterogeneous treatment effects, the bias arises from the comparison between later treated units and earlier treated units that instead serve as the control. The event-study model usually generates reliable estimates as it breaks down treatment effects in different periods. To further mitigate this concern, we employ a doubly-robust DID estimator proposed by Callaway and Sant'Anna (2021). This estimator only compares treated units with never-treated ones serving as controls, hence excluding all the "bad" comparisons. In the appendix (Panel D of Appendix Table C7), we report the aggregated estimates of the average treatment effect on the treated for all timing groups across all periods.

The coefficient estimates for losses are very similar to our main estimates, suggesting that heterogeneous treatment effects depending on the timing of the treatment are not a concern. The estimates for revenue recovery are smaller than our main estimates. This difference in magnitude is likely due to the significant baseline differences in revenue recovery for earlier versus later treated cohorts, possibly resulting in heterogeneous treatment effects. As further analysis, we also estimate event-study models following the approach suggested by Callaway and Sant'Anna (2021) and Sun and Abraham (2021). Results from these alternative estimators exhibit similar patterns to our main results (Appendix Figure C1). The sustained effects on losses suggest a permanent reduction in theft and limited adaptation to the technical intervention via other channels that can be used for stealing such as meter tampering.[26] However, we do not observe a sustained improvement in revenue recovery. This is likely because the cables were intended to prevent theft, but they do not change the tools available to the utility to enforce bill payment. The initial improvements in revenue recovery might reflect customers' fear or belief that enforcement of bill payment may increase with the cables, and the dissipation of effects over time may reflect customers updating their beliefs as they experience additional months of billing post-cable installation.

Contemporaneous Initiatives. Our estimated impact of the cable conversion might be confounded by feeder-line level contemporaneous initiatives. While national or regional policies are common shocks to different feeder-lines and therefore will be absorbed by the IBC-by-month fixed effects, feeder-level time-variant factors still present a challenge. First, there might be contemporary efforts that only target high-loss feeder-lines within IBCs. Second, seasonal patterns might differ across feeder-lines. For example, the utility might spend more effort on maintenance during peak seasons, and maintenance might be more frequent for particular feeder-lines. To mitigate these concerns, we include IBC-by-loss-category-by-month or feeder-by-calendar-month fixed effects to cap-

[26] In additional analyses (not shown), we find no significant impact of cable conversions on claims filed by the utility against customers for damage to low tension cables, service cables, or meters.

ture feeder-level policies within each IBC. The results are similar to our baseline estimates (Panel F of Appendix Table C7).

Additionally, we use data on the timing and location of specific contemporaneous initiatives that may affect losses and were carried out by the utility during times that overlap with the study period. We examine the robustness of our of main results to these initiatives, as described below.

Customer facilitation camps. The utility periodically conducted "camps" in the community with overall intent of increasing goodwill towards the utility. These camps gave people the opportunity to apply for new connections and pay their outstanding bills, and at times also offered free medical services.[27] Using data on the location of these camps, we perform two robustness checks. First, we drop feeders if they have a transformer within a specified distance of camp location (using 300 meter or 500 meter buffers). Second, we create a series of indicators that equal one if a feeder line has a transformer located within 300 or 500 meters, respectively, of a camp location. We then interact those indicators with our ABC treatment indicator and include those in a series of regressions. In both these checks our main results hold (Panels A and B of Appendix Table C8).

Meter Replacements. Using utility-provided data on the location and timing of efforts to replace old and faulty meters, we explore the robustness of our results to the utility's meter replacement drives that were happening contemporaneously with ABC conversions during our study period (Appendix Table C9 and C10). During these drives old and faulty meters were replaced with new meters. Importantly, the new meters were not technologically different from the meters that they were replacing; for example, they were not equipped with smart meter or automatic meter reading capabilities.[28] We use the start date of the meter replacements in a given transformer to identify the earliest month in

[27]The utility conducted a total of 170 customer facilitation camps between 2018-2021. The breakup by year was: 11 (2018), 42 (2019), 54 (2020), and 63 (2021).

[28]Conversations with KE indicate that meter replacement was conducted only on an "as-needed" basis (i.e., when broken or faulty meters were identified during the cable conversion process) for the duration of our study. KE did indicate that more recently, meter replacement had been bundled into the ABC infrastructural upgrades as they felt it was more cost-effective in the long-run.

which a feeder line started having any old and faulty meters replaced. For feeder lines undergoing meter replacements, we restrict our sample to months prior to the first month in which meter replacements were initiated (columns 1 and 2 of Appendix Table C9). We can drop these feeder lines altogether (columns 3 and 4). Or we can add an indicator for meter replacement as a control and also include its interaction with the treatment variable (columns 5 to 8). These additional results suggest that meter replacements are not driving the estimated effect of the theft-resistant cables on losses or revenue recovery. The effect of cable conversion, when combined with meter replacement, on losses is negative which suggests that meter replacement likely curtailed the use of meter tampering as a means to steal electricity. However, there is no additional effect of meter replacement on revenue recovery. Additionally, we estimate the effect of meter replacements alone on losses and revenue recovery and find that meter replacements on their own are not affecting these outcomes significantly either in the period before the cables were installed (pre-ABC) or the period after their installation (post-ABC) (Appendix Table C10).

Project "Sarbulandi." KE instituted a multi-pronged project that encompassed several efforts designed by their regional office (IBCs) to curb theft, improve recoveries and build both customer and employee goodwill. We have described this project in detail in a separate qualitative paper (Ahmad et al., 2021), and summarize it and related robustness checks briefly here. Following the conversion to theft resistant cables, further initiatives such as customer facilitation camps (discussed above) and employee incentives schemes (tied to revenue targets) were carried out to improve bill payments. This effort was decentralized and management in regional offices (IBCs) was responsible for designing and implementing these initiatives. While our checks for customer facilitation camps and meter replacement above help control for the two major initiatives within Project Sarbulandi, we also exploit the difference in timing of Project Sarbulandi across the twelve high loss IBCs to perform a further robustness check on the confounding effect of unobserved contemporaneous initiatives carried out under the project. In the first phase of Project Sarbulandi, which became operational in November 2019, six of the twelve high loss IBCs were selected by KE management to receive these initiatives. The remaining six became eligible in phase 2, which was delayed due to COVID-19 and did not become operational during our sample period.

We find that our main results are robust to all possible exclusions (Appendix Table C11). The size of the treatment effect on losses is very similar and almost identical when looking at treatment effects on phase 1 and phase 2 feeders separately, which suggests that the effect of theft resistant cables (a technical intervention) in reducing losses is similar across these groups despite the occurrence of additional initiatives in phase 1 IBCs. The size of the treatment effect on revenue recovery is smaller without phase 1 feeders (especially when we exclude phase 1 feeders completely) but still significant.

6.2 Mechanisms for Utility Effects

We examine the mechanisms through which loss reduction occurred. First, we assess whether the observed effects on losses reflect a reduction in technical losses. After our analyses indicate that technical losses are not a significant channel (Section 6.2.1), we interpret the changes in losses to be driven by reductions in unbilled consumption. We next examine the potential channels through which unbilled consumption fell and find evidence of both an increase in the number of formal customers (Section 6.2.2) and an increase in the billed units consumed by formal customers (Section 6.2.3). These results are indicative of cables causing both previously fully and partially informal consumers (i.e., those that were using both kundas and formal connections) to shift to formal connections.

6.2.1 Effect of Theft-Resistant Cables on Technical Losses

Are the observed effects explained by a reduction in technical losses? Although data limitations make fully disentangling technical losses from overall T&D losses impossible, we present several pieces of evidence that strongly suggest that reductions in technical losses are not driving the observed effects on losses.

We first estimate the effects of cables on losses in feeder lines that had low losses at baseline. As explained in the background information, KE targeted the installation of theft-resistant cables to feeder lines that were designated as high-loss and very high-loss based on their historical records. As a result of that policy, we expect that most of the feeder lines that were converted to cables will be high loss. However, due to the "ring-fencing" strategy, some low loss feeder lines were converted simply because they were located close to high loss feeders that were converted. Employing these treated lower loss feeders here, we estimate the reduction in technical losses from the cables.

Results from these tests using low-theft feeders are in the first three columns of Table 2. In column 1, we restrict to the sub sample of feeder lines designated as low loss by KE at baseline, which the utility defined as those with past annual aggregated losses below 25%. This is a relatively broad classification and it likely includes some areas where theft does occur. Therefore, in column 2, we further restrict the sample to feeder lines with baseline losses below 10%, which are even less likely to have much theft. In column 3, we restrict to a subsample of feeders that serve industrial or strategic customers (e.g., hospitals, military, and police) and therefore theft is very unlikely to happen. If technical losses were falling post installation, then we should observe overall losses go down in these three subsamples, as theft is presumably low. However, in all three cases, we find no significant effect of theft-resistant cables on losses and the magnitudes of these coefficients are much smaller compared to the main results in Table 1.

As a further check, we use a proxy for technical losses to examine whether feeder lines with higher technical losses respond more to cable conversion, which would indicate a reduction in losses due to reductions in technical losses. We create a technical loss proxy using baseline data on total transformer capacity of each feeder line. Specifically, we calculate the baseline transformer load ratio, which is the fraction of units sent out in a given month to the maximum units that transformer can handle based on its capacity.

Higher values of this load ratio are indicative of higher technical losses. In columns 4 and 5 of Table 2 we use this variable in levels and log interacted with the ABC variable. In column 6, we use the NEPRA defined threshold of 0.8 to identify overloaded feeder lines, which are expected to have higher technical losses. We do not find any evidence that feeder lines with higher technical losses experience a greater reduction in overall losses after the cable conversion.

The fact that the cable conversions occurred in the part of the distribution network that does not account for the major share of technical losses supports the lack of evidence suggesting a significant reduction in technical losses. The program involved installing theft-resistant cables to replace bare wires between the transformers and customer meters. However, technical loss assessments of Pakistani distribution companies suggest that only 26% of the technical losses take place along these lines. Most of the technical loss occurs either in the lines transporting electricity from the grid's substation to the transformer or within the transformer itself, as voltage is stepped down for service.[29]

These findings are also consistent with engineering calculations for cable conversion in Iran, another high loss setting. Analyses by Abdollahi et al. (2020) indicate that technical loss reduction due to ABCs is at most 1.5 percentage points. Taken together these pieces of evidence suggest that at least 6.7 percentage points of our main effect of 8.2 percentage points is not explained by technical loss reduction. Therefore, we interpret the loss reductions as being driven by reductions in unbilled consumption and turn to examine mechanisms related to theft.

[29]We use data from internal reports made available by NEPRA assessing technical losses in different parts of the distribution system. These assessments, which were carried out between 2015-20 for all state owned distribution companies, indicate that only 26% of technical loss occurs in the low tension wires and cables used to distribute electricity between the transformers and the customers. The other three quarters of technical loss occurs elsewhere in the distribution system.

6.2.2 Effects of Theft-resistant Cable Installation on Customer Numbers

Unbilled consumption could fall due to increased formalization of customers. Customers previously connecting to the grid via informal, illegal connections may shift to formal connections at the time theft-resistant cables are installed. We investigate this channel through both event studies and regression analyses.

We perform an event study in which the outcome variable is the number of all types of consumers on a feeder-line over time (Appendix Figure C2). There is no evidence of a statistically significant difference in pre-trends between the treated and untreated feeder-lines. There is a statistically significant increase in the number of customers following the installation of the theft-resistant cables. The number of customers begins to increase starting from the third month after the installation of the theft-resistant cables. This is consistent with the information provided by the utility that stated that the time required, on average, between a connection application being submitted and the connection being approved and functioning was 3 months or longer.

As before, we implement two regression analyses to estimate the impact of theft-resistant cables on the number of consumers. One uses the binary indicator of cable installation as the treatment variable and the other uses the proportion of transformers in a feeder covered by theft-resistant cables as the measure of treatment intensity. In Table 3 column 1, the outcome variable is the number of consumers – of all types – in each feeder-line. We see a significant effect of theft-resistant cables on the total consumers in both Panel A (using the ABC binary treatment indicator) and Panel B (using the treatment intensity variable). Columns 2 through 6 in the table show the estimated impacts of the cables on different categories of consumers (agricultural, bulk, commercial, industrial, and residential). We find that overall the cable installation led to a 161 customer increase at the feeder-line level (column 1) and that these changes were driven primarily by an increase in residential consumers (column 6). Results using alternative model specifications have similar findings (Appendix Table C12).[30]

6.2.3 Consumers Bills for Electricity Services

Event studies indicate that, following the installation of theft-resistant cables, both residential consumers' quantity of billed units and the monetary billed amount increased significantly (Appendix Figure C3). This is consistent with a reduction in kundas and an increase in consumption of electricity services through formal grid connections. These came with reductions in the probability of customers not paying their bill and an increase in the payment ratio (the proportion of the billed amount paid for the month), which coincides with the increases in bill payment found in the feeder-level analysis. Lastly, there is evidence of a reduction in irregular billing and indicators of theft.[31]

The DID regression results in Table 4 provide further insights. Panel A shows the average treatment effect, similar to those in the event studies. With our binary treatment variable indicating theft-resistant cable installation, we interpret these coefficients as the impact of a bare wire from a transformer being converter to these theft-resistant cables. In columns 1 and 2, the outcome variables are the logarithm of billed units (kWh) and billed monetary amounts (rupees). Results indicate that conversion led to a 9% increase in kWh of billed units (column 1) and a 9.8% increase in billed amount (column 2). In addition, the probability of a customer not paying their monthly electricity bill on time decreased by 5.2 percentage points (column 3), and the ratio of monthly billed quantity paid increased by 1.6 percentage points (column 4). Finally, the probability of an irregular bill and the probability of theft during a month reduced by 11.1 and 3.8 percentage points, respectively (equal to about a 55% and 76% decrease in probability when compared to the outcome means).[32]

[30]We use the raw numbers for our main model specification given the recent critiques on log-like measures (Chen and Roth, 2023; Mullahy and Norton, 2022). In Table C12, we report results from various transformations and find that our results are unchanged.

[31]In Appendix Figure C4 and C5, we present event-study model estimates following the approach suggested by Callaway and Sant'Anna (2021) and Sun and Abraham (2021). The results are similar.

[32]We define the variable "Irregular Bills" as any billing category other than normal. Irregular bills arise

Panel B shows heterogeneity by expenditure group. Interestingly, the effects of the theft-resistant cables on the low-expenditure and high-expenditure groups are of similar magnitude for all outcomes except one. In column 5, the households with expenditures greater than $2 per day are significantly less likely to have irregular bills within a month than those households with expenditures less than $2 per day.

6.3 Utility's Cost-Benefit Calculations

To put the utility's benefits from this infrastructure upgrade in context, in this section we compare those benefits with the costs of the theft-resistant cable installation and calculate the net present value of upgrading the distribution system. In the paragraphs that follow, we summarize the steps involved in these NPV calculations and present the results of the exercise. Full details on these calculations are provided in Appendix D.

6.3.1 Costs of Theft-Resistant Cables

First, using data provided by KE, we create four cost scenarios, which allow us to put bounds on the overall expected costs of theft-resistant cables. The costs potentially included in our scenario calculations are: the costs of purchasing the theft-resistant cables themselves, the labor costs for replacing the old bare wires with the cables, the cost of purchasing – in addition to the theft-resistant cables – new meters to replace those old meters installed on the premises of the customer, and the additional labor cost of replacing those old meters.[33]

These scenarios result in a range of estimated costs per customer. Scenario 1 includes only the costs of theft-resistant cables themselves, whereas Scenario 2 captures both the

if the meter stops working or becomes faulty, if there are errors in recording units or calculating bills, and when there is a case of theft or kunda detection by KE. The variable "Thefts" is defined using the billing category which specifies irregular bills due to theft detection. It is then a subset of larger category of irregular billing.

[33] As previously-mentioned, KE sometimes replaced old, faulty meters with new meters at the time when theft-resistant cable conversion occurred. These new meters are the same technology as the old ones that they replaced (i.e., they are not a more advanced technology, such as prepaid meters or smart meters).

cost of theft-resistant cables and of labor (per transformer) required to install them. The labor expenses are not necessarily specific to this infrastructure upgrade – as even bare wire need to be regularly replaced – and therefore a scenario (one) in which they are omitted is reasonable. Scenarios 3 and 4 extend the first two to encapsulate the costs of also replacing old meters, with the former including just material costs for purchasing theft-resistant cables and new meters and the latter covering those costs plus the labor costs for installation of both. The estimated costs to the utility are between 16,389 PKR per customer (Scenario 1) and 33,630 PKR per customer (Scenario 4) (all scenarios shown in Appendix Table D1). For simplicity, we assume these costs all occur upfront in year 0.

6.3.2 Benefits from Theft-Resistant Cables

To approximate the benefits to the utility, we use the change in customer payments following the conversion to theft-resistant cables, based on the estimated increase in the monetary billed amount from Table 4. These estimates will allow us to calculate the present value of the upgrade.[34] We divide these benefits per year by the number of consumers in high-loss areas and calculate a benefit to the utility of 5,729 PKR per-consumer per year.

There are two interesting sources of uncertainty in determining the magnitude of the expected benefits from the intervention: the discount rate and the lifespan over which the technology is expected to function. For this reason, we present calculations of benefits for ranges of both discount rates and expected lifespans. First, we calculate the utility's discounted benefits over a range of discount rates (8%, 10%, and 12%), which are informed by KIBOR Rates for this time period.[35] Further, given the expected lifespan for theft-resistant cables in Karachi is less than the average expected lifespan globally due to local conditions (10 years, per conversations with KE, instead of between 15 and 20 years), we

[34]We note, however, these estimates are calculated from KE's conversion of high loss feeder lines to theft-resistant cables and therefore they cannot be extrapolated to low loss feeders or settings.

[35]KIBOR rates refer to the Karachi Interbank Offered Rate, which is the daily rate at which banks offer funds to each other. KIBOR is then used as the benchmark for lending to the corporate sector (State Bank of Pakistan, 2023).

calculate the benefits for a range of lifespans.

We find that the range of discounted benefits per customer to be between 32,373 PKR (10 year lifespan with 12% discount rate) and 56,253 PKR per customer (20 year lifespan with 8% discount rate), which is between 216 and 375 USD, respectively. Full results of the discounted benefits are in the Appendix (Table D2).

6.3.3 Net Present Value of Theft-Resistant Cables

Lastly, we compare the benefits, as calculated for these different time horizons with varying discount rates, with the costs of the intervention to calculate the net present value of the theft-resistant cables. These net present value calculations are presented in Table 5 (results converted to USD are in the Appendix, Table D4). All of the scenarios result in positive NPV, except the most conservative calculation, which is quite unlikely (benefits calculated for a 10-year lifespan using a 12% discount rate and the highest cost scenario).

7 Effects on Consumers

Thus far, the evidence indicates that this technical solution – theft-resistant cables – is a beneficial investment for the electricity utility. In this section, we shift to examining the effects of theft-resistant cables on consumers in the areas in which those cables were installed. We show that both the hours of load shedding and consumers' complaints to the utility decrease in these areas. However, a more nuanced analysis indicates an increase in complaints to the utility regarding billing issues.

Using our cross-sectional survey data, we compliment the causal evidence with correlational analyses that shed light on how these effects manifest within households.

7.1 Electricity Services

During the study period (and years prior), the electricity utility employed a load shedding strategy that allocated more hours of outages to areas with higher losses. To do so, feeder-lines were assigned to load shedding categories based on their losses in the prior months. If a neighborhood served by a feeder-line reduced its losses, then the feeder-line could move to a better load shedding category with fewer hours of outages allocated per day.

7.1.1 Hours of Load Shedding

As we showed in Section 6, the utility's financial indicators improved – unbilled consumption fell and bill recovery increased – following the installation of the theft-resistant cables. If this reduction in losses was sufficient to shift the feeder-line to a better category, then we should see a decline in the hours of load shedding.

Leveraging the utility's record on these planned outages, we estimate the causal effect of the cables on the average hours of load shedding per day in a month. We perform the analyses in levels and logs and present results in Table 6.

The first two columns use the whole sample, whereas the last two columns focus on high-loss IBC regions. We find unambiguous evidence of reduced load shedding following cable conversion, indicating that households are scheduled to receive more hours of electricity services per day. The coefficient estimate in Panel A, Column (3) suggests that, on average, cable conversion decreased daily load shedding by 0.4 hours. The impact is increasing in conversion ratio in both the whole sample (column 2) and the high-loss IBC sample (column 4). As robustness checks, we use the inverse hyperbolic sine of the average hours of electricity supply per day and get similar results (Appendix Table C13).

We supplement these causal findings with correlational analyses. Given that our residential consumer survey is cross-sectional, we compare households located in feeder lines with theft-resistant cables installed with households in feeder lines without those cables installed. Table 7 presents differences in reported hours of load shedding for households in summer (column 1) and winter (column 2). Consistent with our causal estimates indicating a decline in load shedding (Table 6), households reported fewer hours per day of load shedding in both the summer and winter in the cabled areas, relative to the non-cabled areas. The estimated reduction in load shedding is approximately one fewer hour of load shedding in areas with theft-resistant cables, depending on the season. Notably, the mean reported load shedding in the control group is 8.5 hours per day in the summer and 6.9 hours in the winter.

It is possible that some of the differences in reported outages shown in Table 7 – between areas with theft-resistance cables installed and those without – are due to the theft-resistant cables also affecting unplanned outages (not just load shedding). ABCs could reduce load (given we see a reduction in the quantity of electricity sent out to treated feeder lines in Appendix Table F7) and therefore also reduce the incidence of unplanned outages. For example, Carranza and Meeks (2021) illustrate how overloaded distribution infrastructure is a source of unplanned outages. We unfortunately cannot shed more light on that channel for our current study, without additional data.

Lastly, we note that these effects on the hours of load shedding are linked to the utility's policy on and allocation of load shedding based on losses (as detailed in Appendix A1). Theft resistant cables would not necessarily have the same effect on load shedding hours in a location without a similar policy.

7.1.2 Consumption of Electricity Services

Given theft-resistant cables led to fewer hours of load shedding, we anticipate that this may translate into effects on the consumption of electricity services. Fewer hours of load shedding means that consumers can use appliances and consume the services that they provide for more hours per day. One summary measure of consumption of electricity services is household electricity expenditures. Table 8 shows that households in areas with cables installed have significantly higher electricity expenditures both per household (column 5 Panel A) and per capita within a household (column 5 Panel B). Interestingly, this does not appear to mean lower non-electricity expenditures (column 3), but slightly (albeit insignificantly) higher total expenses (column 1).

These higher electricity expenditures could come from increased consumption of electricity services on the intensive (greater use of the appliances that they own) or extensive (adding new appliances) margins. Results in Table 7 indicate that cables are correlated with changes along both margins: households in cabled feeder lines have 0.51 more appliances (column 3) and use their appliances 3.5 more hours per day (column 4), on average, than those without cables installed.

Our analyses are limited by the fact that both our survey data and the administrative billing data are limited to formal customers. We do not observe consumers who are never formal customers. We are unable to definitively identify those customers who were previously informal and are now formalized, as new accounts created with KE after the cable conversion may be previously informal customers shifting to formal connections or they may simply be new properties getting connected for the first time. Moreover, even the customers who were always formal may have been using kundas for some portion of their consumption prior to the cable conversion.

With these limitations in mind, we carry out exploratory analysis to shed light on how the consumption of previously informal customers and incumbent customers might have been impacted by the theft-resistant cables. This analysis requires multiple assumptions. First, we must assume that all those new customers who joined within six months of cable conversions were previously informal. Second, we must assume that the incumbent customers were not stealing. Using data on the date the customers get a connection, we identify the group of new and (presumably) previously informal customers. We plot the distribution of monthly billed units and monthly average billed units for the new customers relative to the distribution of incumbent customers and find that the consumption distribution of the new customers lies to the left of the distribution for incumbent customers (Appendix Figure C6). This suggests that formalization is driven by the poorest of the poor converting to formal connections. Interestingly, the distribution of both monthly usage and average monthly usage for new users peak below 200 units, which is the government-designated threshold for protected consumers (i.e. consumers whose variable cost tariffs are highly subsidized by the government).[36] This further highlights that the intervention may have had the greatest effect on the poorest households.

We also carry out quantile regression analysis to explore the impact of cable conversions across the distribution of billed units. Results from the quantile regression analysis (Appendix Table C15) suggest that cable conversion had higher effects at lower percentiles of the distribution of billed units, both within and across consumers (Panel A and B respectively). The larger effects might be driven by substitution away from kundas to formal consumption, consistent with our previous finding that newly formalized customers are in the lower part of the distribution. However, the results are only suggestive, as they may also be driven by factors other than formalization (e.g. by a reduction in rationing that affected poorer households more if they lacked back-up systems). Finally, we note that this exploratory finding of formalization affecting poorer households also suggests that policy makers may need to revisit the tariff structure, as those with the highest subsidy, were seemingly more likely to use informal channels. The greater demand for informal connections in this group might also reflect lack of trust in the utility due to perceptions of poor service delivery at high cost.

7.2 Perceptions of Billing

With the installation of theft-resistant making illegal connections more difficult, some households are either changing from a kunda to a formal connection or shifting from splitting their consumption between a kunda and formal connection to having all their

[36] A protected consumer is defined as a household whose monthly consumption remains below 200 units for 6 months continuously.

consumption billed based on a meter reading (or generally having their consumption billed based on the regulator-set tariff schedule). For these reasons, many households are paying more than they did previously (prior to the cable conversion) for their consumption of electricity services. As a result, the utility's consumers may be disgruntled, unhappy with the amount that they owe, or just simply confused by their monthly bill and how it is calculated. In this section, we investigate how the theft-resistant cables may affect consumers' actions towards and beliefs about the utility.

7.2.1 Complaints to the Utility

The most direct indicator that we have to measure consumers' unhappiness and how it is affected by the cable installation is through the consumers' direct complaints to the utility. Consumers may submit formal complaints to the utility for a number of reasons (e.g., complaints regarding deterioration of service quality or disputes of bills). We investigate whether any of these were impacted by the theft-resistant cables in this subsection.

We use the utility's data on consumer complaints at the feeder-line level, and the type of complaints filed, to estimate impacts of theft-resistant cables on these outcome measures. Regression results are presented in Table 9, with Panel A reporting results where the outcome variable is the number of complaints and Panel B normalizing these results relative to the number of consumers at a feeder line. Estimation results across the two panels suggest that consumer complaints overall decrease with cable conversion, which is mainly driven by the decline in technical complaints and is consistent with improvements in service quality. Complaints about billing also increase, which is in line with our survey results showing that consumers in treated areas distrust KE billing more than those in non-treated areas (see next section). We also report estimation results using alternative measures of the outcomes, and find similar results (Appendix Table C14).

7.2.2 Beliefs about Billing

Lastly, we use data from survey questions designed to elicit respondents' beliefs and perceptions to understand if there are differences across treated and non-treated households with respect to the electricity utility, load shedding, and billing/bill payment. Results are presented in Figure 3. Households in areas with theft-resistant cables are, on average, less likely to believe that their electricity bills accurately reflect their consumption and more likely to report that bill errors are a concern. These consumers are, however, also less likely to believe that electricity quality issues (both electricity shortage and load shedding) are problems, which is consistent with our earlier results.

8 Conclusions

The International Energy Agency (2020) expects that between 2020 and 2030, 16 million kilometers of existing electricity distribution lines need to be *replaced*, with approximately 60% of these replacement needs located in low and lower-middle income countries. This will require vast financial investments by distribution companies worldwide. And this does not even include the investments needed for the *newly-constructed* distribution lines in settings that are being electrified for the first time – as of 2020, 733 million people around the world still were without electricity (United Nations, 2022). Taken together, substantial investments in distribution infrastructure are expected in the near future, as distribution companies face the decision as to whether to invest in bare wires or more expensive theft-resistant cables.

In this paper, we present evidence on the impacts of an upgrade to distribution lines in Karachi, Pakistan that prevented illegal connections to the grid. We find that the theft-resistant cable conversion both significantly reduced unbilled consumption (theft) and increased bill payment. We find evidence that the cables achieved these impacts by increasing the total number of formal metered residential customers, increasing the quantity of billed units (and therefore the billed monetary amounts) as well as the payment ratio, while decreasing irregular bill payment and indicators of theft. Together, these results are indicative of these cables making illegal connections to the distribution wires more difficult and, as a result, more customers becoming formal customers of the utility. The results for revenue recovery (a measure of bill payment), show a dissipating effect and highlight the need for future research to study the relationship between technical and behavioral interventions designed to improve bill payment behavior.

Finally, our consumer related results suggest some benefits due to improvements in consumption of electricity services and reliability, there is dissatisfaction with billing. To the extent that the intervention formalized mostly poorer customers, this suggests that such interventions ought to be paired with additional tariff and social assistance reforms for the poorest households.

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Figures and Tables

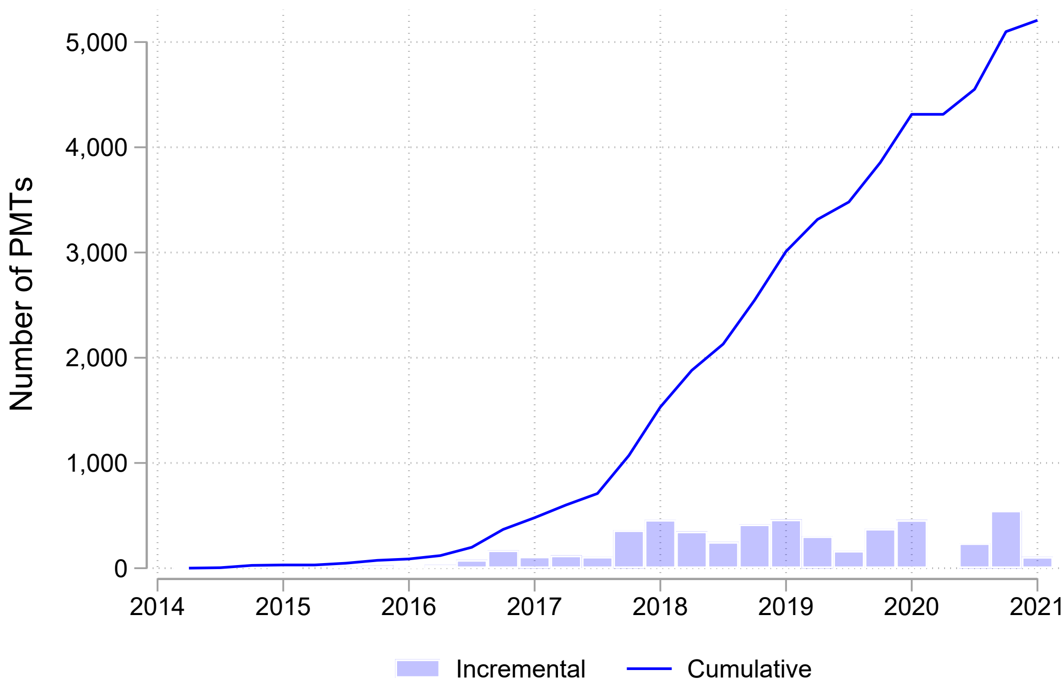

Figure 1: Theft-resistant Cable Installation Over Time

Notes: This figure shows the incremental and cumulative number of transformers with ABCs installed over time in Karachi, Pakistan.

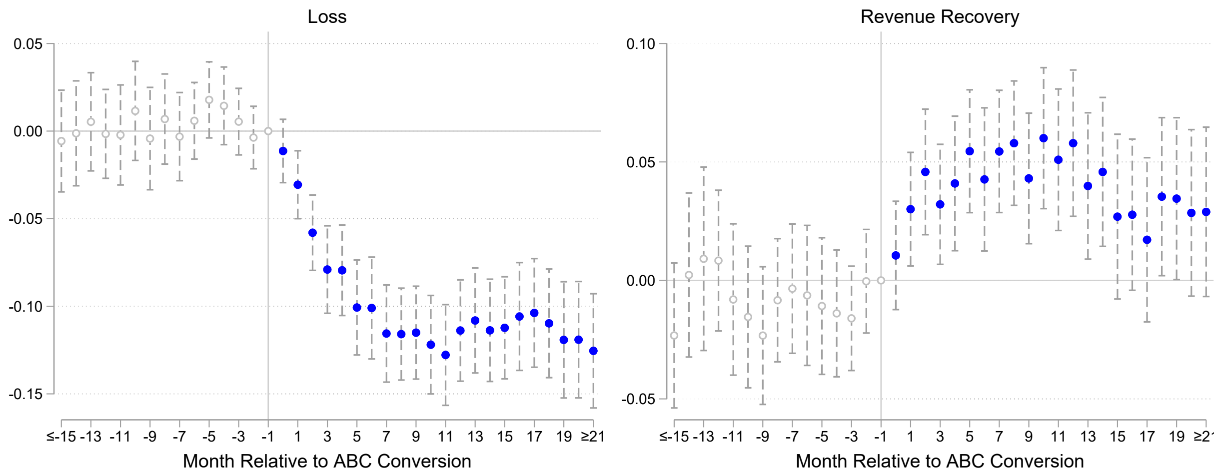

Figure 2: Event-Study Estimates: Impacts of Theft-resistant Cables on Losses and Revenue Recovery

Notes: The figure shows the coefficients and their 95% confidence intervals from an event-study regression estimating the impact of ABC installation on losses and the revenue recovery rate. Data are at the feeder level on a monthly basis. Regressions include IBC-by-month and feeder fixed effects. One month prior to the ABC installation (-1) is the reference group, and the corresponding coefficient is normalized to zero. Standard errors are clustered at the feeder level.

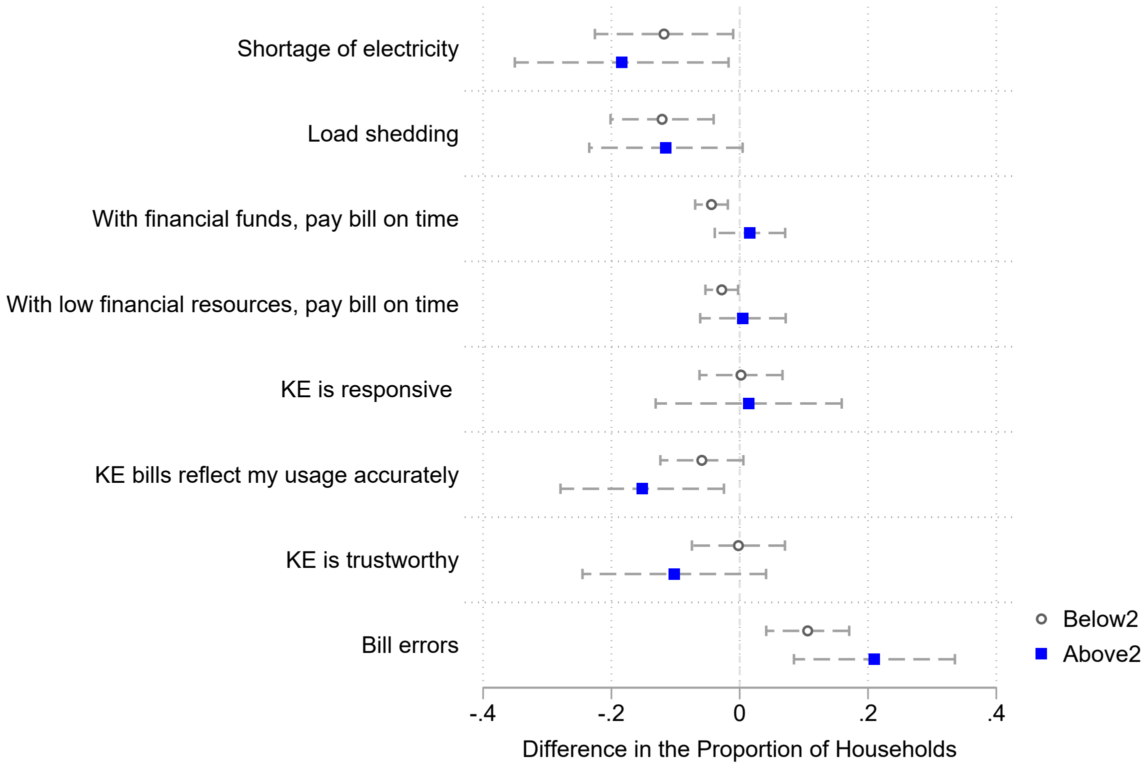

Figure 3: Differences in Household Beliefs Across Cabled and Non-cabled Areas

Notes: The figure plots coefficients and their 95% confidence intervals from regressing outcome variables on the interactions between ABC (a binary dummy that equals 1 if the household is served by a transformer with ABCs installed) and two categorical income variables (Above2 and Below2). The variable Above2 equals 1 if the household's expense per capita is above $2 each day, and the variable Below2 equals 1 if the household's expense per capita is below $2 each day. Data were collected via our household survey implemented in late 2021, asking respondents to indicate whether they agreed or disagreed with the belief statements. The outcome variables here are binary indicators equaling 1 if the respondent indicated some level of agreement (mildly agree to strongly agree) with the statement and zero otherwise. Regressions include control variables: total number of family members, number of rooms, years in the neighborhood, indicators for house ownership, indicators for owning a car, indicators for having financial accounts, expenditures on food items, and binary indicators for household income categories. Standard errors are clustered at the transformer level.

Table 1: Effect of Theft-Resistant Cables on Losses and Revenue Recovery

	Monthly		Quarterly	
	Loss	Revenue Recovery	Loss	Revenue Recovery
	(1)	(2)	(3)	(4)
Panel A: DID Estimates				
ABC	-0.082***	0.052***	-0.062***	0.050***
	(0.009)	(0.009)	(0.008)	(0.009)
Panel B: Intensity of Treatment				
ABC Ratio	-0.176***	0.090***	-0.175***	0.105***
	(0.013)	(0.013)	(0.013)	(0.013)
Control Mean	0.260	0.792	0.243	0.813
Observations	47,575	37,353	18,219	15,157
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓		
IBC-Quarter FE			✓	✓

Notes: Data are at the feeder-line level. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of transformers with ABCs installed divided by the number of total transformers in a feeder-line. All regressions include feeder and IBC-by-month or IBC-by-quarter fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 2: Mechanisms: The Role of Technical Losses

Dep. Var.:	Loss					
	(1)	(2)	(3)	(4)	(5)	(6)
ABC	-0.029	-0.025	0.027	-0.073***	-0.089***	-0.081***
	(0.018)	(0.037)	(0.018)	(0.028)	(0.017)	(0.009)
ABC $\times$ Load Ratio				-0.015		
				(0.045)		
ABC $\times$ ln(Load Ratio)					-0.013	
					(0.024)	
ABC $\times$ I[Overload]						-0.004
						(0.022)
Restrict to Low-Loss Feeder Lines	✓					
Restrict to Feeder Lines with Base Loss $<$ 0.1		✓				
Restrict to Industry/Strategic Feeder Lines			✓			
Number of Feeders	809	327	443	1,687	1,687	1,687
Observations	19,944	7,446	9,095	45,710	45,710	45,710

Notes: Data are at the feeder-line level. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. Column (1) restricts to feeder lines that are classified as low loss by KE (losses $<$0.25) in January 2018, the first month of our sample. Column (2) restricts to feeder lines whose average losses over January 2018 to June 2018 are less than 0.1. Column (3) restricts to feeder lines that are categorized as industry or strategic by KE. Columns (4)-(6) use the whole sample. Load Ratio is the average ratio of monthly electricity supply relative to the total electricity units that a feeder line can handle given the transformer capacity. We measure the load ratio for each feeder line using the 2017 monthly electricity supply data and by taking the average over the 12 months. I[Overload] is an indicator for whether the feeder line is overloaded with the load ratio that is higher than 80%. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: Mechanisms: Effects of Theft-Resistant Cables on Consumer Numbers

Number of Consumer	Total (1)	Agriculture (2)	Bulk (3)	Commerce (4)	Industry (5)	Resident (6)
Panel A: DID Estimates						
ABC	161.586***	0.032	-0.005	2.227	-0.896	160.229***
	(46.574)	(0.152)	(0.007)	(5.564)	(0.813)	(43.496)
Panel B: Intensity of Treatment						
ABC Ratio	436.463***	-0.035	-0.009	4.154	-2.014	434.367***
	(60.565)	(0.170)	(0.009)	(7.383)	(1.251)	(55.626)
Outcome Mean	1,582.96	1.24	0.09	263.41	11.71	1,306.51
Observations	67,602	67,602	67,602	67,602	67,602	67,602
Feeder-line FE	✓	✓	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓	✓	✓

Notes: Data cover the period between June 2018 and March 2021. The outcome variable is the number of consumers in each feeder-line. Columns 2–6 refer to different consumer categories. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of transformers with ABCs installed divided by the total number of transformers in a feeder-line. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Mechanisms: Effect of Theft-Resistant Cables on Customer Behaviors

	ln(Billed Units) (1)	ln(Billed Amount) (2)	Not Pay (3)	Payment Ratio (4)	Irregular Bills (5)	Theft (6)
Panel A: Average Treatment Effect						
ABC	0.090***	0.098***	−0.052***	0.016***	−0.111***	−0.038***
	(0.024)	(0.029)	(0.012)	(0.005)	(0.021)	(0.008)
Panel B: Heterogeneity by Expenditure Groups						
ABC × Below2	0.090***	0.096***	−0.050***	0.017***	−0.106***	−0.038***
	(0.024)	(0.030)	(0.012)	(0.005)	(0.020)	(0.008)
ABC × Above2	0.086	0.118*	−0.076***	0.014	−0.159***	−0.039***
	(0.060)	(0.070)	(0.027)	(0.011)	(0.041)	(0.015)
Outcome Mean	241.05	3,369.08	0.33	0.20	0.20	0.05
Observations	88,296	88,296	88,296	88,296	88,296	88,296
Number of Households	3047	3047	3047	3047	3047	3047
Customer FE	✓	✓	✓	✓	✓	✓
Month FE	✓	✓	✓	✓	✓	✓
Transformer-M-of-Yr FE	✓	✓	✓	✓	✓	✓

Notes: Customer-level data are provided by KE for June 2018 through August 2021. These residential customers are all "active" accounts within the KE system as of August 2021. The outcome variables include billed electricity units (in log), billed electricity amount (in log), an indicator for whether the customer does not pay electricity bills on time, the proportion of payment relative to the total due to KE (payment ratio), an indicator for whether there are irregular bills in that month, and an indicator for whether there are any irregular bills specifically due to theft in that month. ABC is a binary dummy that equals 1 if the household is served by a transformer that has ABCs installed already. The indicator Above2 equals 1 if the household's expense per capita is above $2 each day, and the indicator Below2 equals 1 if the household's expense per capita is below $2 each day. All regressions include customer, month, and transformer-by-month-of-year fixed effects. Standard errors are clustered at the transformer level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: Net Present Value per Consumer: Costs versus Benefits of Cable Conversion

Variations in lifespans and discount rates	Cable Cost Scenarios (PKR) 1	2	3	4
Panel A: 20-year lifespan				
8%	39863.5	35766.2	31337.1	22622.2
10%	32388.9	28291.6	23862.5	15147.6
12%	26406.7	22309.4	17880.3	9165.3
Panel B: 15-year lifespan				
8%	32652.0	28554.7	24125.6	15410.7
10%	27189.5	23092.2	18663.1	9948.2
12%	22633.4	18536.1	14106.9	5392.0
Panel C: 10-year lifespan				
8%	22055.9	17958.6	13529.5	4814.6
10%	18815.8	14718.5	10289.4	1574.5
12%	15983.5	11886.2	7457.1	-1257.8

Notes: All values are in PKR per customer. Discount rates are based on Kibor Rates documented by the State Bank of Pakistan for this time period. The expected lifespan of theft-resistant cables installed in Karachi (per KE) is 10 years.

Table 6: Effect of Theft-resistant Cables on Hours of Electricity Supply

Dep. Var.:	Average Hours of Electricity Supply Per Day			
	Whole Sample		High-Loss IBCs	
	(1)	(2)	(3)	(4)
Panel A: Raw Levels				
ABC	0.396***		0.402***	
	(0.087)		(0.089)	
ABC Ratio		1.023***		1.057***
		(0.123)		(0.125)
Panel B: Logs				
ABC	0.021***		0.021***	
	(0.004)		(0.005)	
ABC Ratio		0.054***		0.056***
		(0.006)		(0.007)
Outcome Mean	19.93	19.93	18.01	18.01
Observations	34,997	34,997	12,298	12,298
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓

Notes: Data are at the feeder-line level on a monthly basis. The outcome variable is average hours of electricity supply per day in a month (measured in raw levels and logs). ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of transformers with ABCs installed divided by the number of total transformers in a feeder-line. All regressions include feeder and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Evidence on Household-Reported Service Quality and Appliances

	Daily Hours of Load Shedding/Power Cuts		Total Number of Appliances	Total Hours of Daily Usage
	Summer	Winter		
	(1)	(2)	(3)	(4)
ABC	−1.185***	−1.005***	0.486***	3.530***
	(0.266)	(0.320)	(0.153)	(0.847)
Control Mean	8.541	6.872	6.833	18.409
Observations	3,068	3,068	3,068	3,068
Control	✓	✓	✓	✓
IBC FE	✓	✓	✓	✓

Notes: Outcome variables are collected via our household survey implemented in late 2021. ABC is a binary dummy that equals 1 if the household is served by a transformer with ABCs installed. Control variables include the total number of family members, number of rooms, years in the neighborhood, indicators for house ownership, indicators for owning a car, and indicators for having financial accounts. Standard errors are clustered at the transformer level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: Effect of Theft-Resistant Cables on Household Expenditures

Expenditures (log)	Total		Non-Electricity		Electricity	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Per Household						
ABC	0.063**		0.031		0.250***	
	(0.031)		(0.036)		(0.046)	
ABC × Below2		0.061**		0.020		0.254***
		(0.028)		(0.034)		(0.048)
ABC × Above2		-0.135		-0.054		0.078
		(0.089)		(0.090)		(0.121)
Outcome Mean	33,631	33,631	28,569	28,569	5,061	5,061
Panel B. Per Capita						
ABC						
	0.067*		0.031		0.276***	
	(0.037)		(0.040)		(0.058)	
ABC × Below2		0.054		0.009		0.267***
		(0.033)		(0.036)		(0.059)
ABC × Above2		-0.123		-0.047		0.120
		(0.075)		(0.074)		(0.132)
Outcome Mean	5,698	5,698	4,763	4,763	935	935
Observations	3,001	3,001	3,001	3,001	3,001	3,001

Notes: Expenditures are in Pakistani rupees and the exchange rate at the time was approximately 1 USD = 170 rupees. Outcome variables are measured in logs and are collected via our household survey implemented in late 2021. ABC is a binary dummy that equals 1 if the household is served by a transformer with ABCs installed. All columns include IBC fixed effects and control variables (total number of family members, number of rooms, years in the neighborhood, indicators for house owners, indicators for owning a car, and indicators for having financial accounts). We only add the number of family members to the list of control variables in Panel A. Above2 = 1 if the household's expense per capita is above \$2 each day and Below2 = 1 if the household's expense per capita is below \$2 each day. Standard errors are clustered at the transformer level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 9: Effect of Theft-resistant Cables on Consumer Complaints

Number of Complaints	All (1)	Bill Complaints (2)	Service Requests (3)	Technical Complaints (4)
Panel A: Total Measures				
ABC	-28.894***	2.905***	3.846*	-35.644***
	(4.295)	(0.458)	(2.292)	(3.853)
Outcome Mean	85.58	5.48	1.73	12.32
Panel B: Per Consumer Measures				
ABC	-0.016***	0.001***	0.002*	-0.019***
	(0.002)	(0.000)	(0.001)	(0.002)
Outcome Mean	0.264	0.011	0.086	0.166
Observations	71,918	71,918	71,918	71,918
Control	✓	✓	✓	✓
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓

Notes: Data are at the feeder-line level on a monthly basis. The outcome variable is the number of consumer complaints, including all types of complaints, bill complaints, service requests, and technical complaints. In Panel A, we add consumer number as a control variable. In Panel B, we use per-consumer measures, defined as the number of complaints divided by the number of consumers covered by a feeder-line. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

ONLINE APPENDIX

The Economic and Environmental Effects of Making Electricity Infrastructure Excludable

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A Background on Electricity Distribution

A1 Electricity Distribution and Load Shedding

Load shedding is a type of disruption in the distribution of electricity that is not uncommon in many low and lower-middle income countries. When load shedding occurs in a particular area there is no electricity being delivered to that location (e.g., along particular feeder lines of the distribution system).[37] Load shedding can be planned (and potentially announced to the utility's customers before the disruption begins) or unplanned (and therefore also unannounced).

Crucial for our study, Karachi Electric's load shedding policies remained unchanged over the entire duration of our study period, which covers January 2018 to October 2020. Nonetheless, it is helpful to understand the utility's load shedding policy that was in existence throughout the study period.

In a broad sense, utilities resort to load shedding when the electricity supply does not meet demand. However, there are multiple reasons why supply might not meet demand and these reasons vary across settings. In some settings, the electricity supply is limited due to the generators' physical plant capacity constraints and this causes a gap between supply and demand. However, there are places – such as in Pakistan – where the electricity supply is limited not by the generators' plant capacity itself, but rather by the utility's ability to purchase the imported fossil fuels necessary to generate the electricity. Electricity utilities in Pakistan, including Karachi Electric, face generation constraints associated with such difficulties purchasing fuels and that is the constraint restricting supply (Ali, Gaibulloev and Younas, 2023).

Due to this constraint, and as described in detail below, KE assigns load shedding at a feeder line according to that particular feeder's losses. In conversations in 2023, Karachi Electric informed that any decrease in load shedding due to lower losses does not necessitate an associated re-arrangement of power that requires increases in load shedding elsewhere. Rather, the additional hours of electricity service delivered to areas where losses have decreased requires that the utility purchase more fuel for electricity generation, but this is possible because losses decreased and the utility is recovering more money per unit of electricity delivered.

The intuition is as follows. By delivering electricity to areas where losses are low, the utility is able to cover the costs of the fuel purchases required to generate that electricity. Supplying electricity to areas where losses are high, the electricity utility cannot cover the cost of the fuel purchases associated with that generation. Supplying electricity to high loss areas increases the utility's debt and makes it more difficult to purchase additional fuel for future electricity generation. Load shedding based on Aggregate, Technical, and Commercial (AT&C) losses, is an effort to limit adding to the utility debt. When load shedding is due to fuel purchasing constraints – not physical plant generation capacity constraints – a decrease in losses in a particular area can mean that the utility is able to purchase more fuel and provide that area with additional hours of electricity services,

[37] Disruptions in electricity services due to load shedding are different than unplanned outages that occur due to breakage within transmission and distribution systems.

without requiring a decrease in hours of electricity supplied to other parts of the distribution network.

Ali, Gaibulloev and Younas (2023) detail Karachi Electric's load shedding policy in the years leading up to our study period (2010-2018). Since 2010, Karachi Electric has allocated load shedding based on the concept of rewarding good behavior (i.e., low theft and therefore low loss feeders have no load shedding) and reprimanding bad behavior (i.e., medium and high theft and therefore medium and high loss feeders are assigned increasingly more hours of load shedding per day) through the allocation of hours of load shedding outages (Ali, Gaibulloev and Younas, 2023). The idea is that feeder lines with increasingly higher average losses will have more hours of load shedding per day. Because the load shedding occurs at the feeder level, all utility customers served by that feeder – both those that fully pay for electricity and those that do not – will be affected by the disruption in electricity service that occurs during a period of load shedding (NEPRA, 2022*b*).

To implement their load shedding regime, KE first calculates for each feeder the Aggregate, Technical, and Commercial (AT&C) losses, using the formula

$$\text{AT\&C} = 1 - \text{RR}(1 - \text{Loss}),$$

where RR and Loss are that feeder-line's Revenue Recovery and line-losses for the month. Karachi Electric sets categories based on the average AT&C of a feeder line in the twelve months prior and then allocates load shedding accordingly. These categories and the designated hours of load shedding per day are shown in Table A1. To allow feeder lines to move up (or down) in the load shedding categories, every quarter the utility recalculates losses using a twelve month rolling average and updates the allocations accordingly (Ali, Gaibulloev and Younas, 2023). The table makes it evident that any changes in load shedding allocation are based purely on the losses of the individual feeder line; a feeder's load shedding is not affected by other feeders.

Anecdotal evidence suggests that residents of Karachi are generally aware that load shedding is correlated with losses and that neighborhoods with higher losses have more hours of load shedding per day. In fact, Pakistan's regulatory agency in a 2022 press release stated that it noted high volumes of consumer complaints regarding AT&C based load shedding for Karachi Electric as well as 4 additional distribution companies serving other cities within the country (NEPRA, 2022*b*).

To the best of our knowledge, these load shedding assignments are not publicly available or published anywhere by the utility (e.g., they are not posted to the utility's website). It is not surprising that a utility would not widely advertise such details, given load shedding is very unpopular among customers. We know based on the regulator's information in the above-mentioned press release that, KE is not the only utility in the country implementing such AT&C based load shedding; at least 5 of the 11 distribution companies in the country are using such processes to allocate load shedding. However, this dearth of information makes it difficult to determine the extent to which load shedding allocations based on losses are commonly employed elsewhere.

To understand whether loading shedding is allocated according to losses in other developing countries – and knowing that these policies might not necessarily be widely

Table A1: Utility Allocation of Load Shedding Hours According to Average Feeder Line Losses

Feeder Line Loss Category	Low	Medium	High	Very High
AT&C losses	$< 25\%$	25-35%	35-50%	$> 50\%$
Hours per day of load shedding allocated	0	3	6	7.5

Notes: The load shedding allocations in this table are by feeder line and were in place from 2010 through 2022. AT&C losses refers to an index of losses constructed by KE that combines feeder level losses and revenue recovery into a single variable. According to Ali, Gaibulloev and Younas (2023) the utility allocated load shedding by these thresholds in 2010 and this continued through 2018. Our team's recent communications with the utility indicate that these exact thresholds and allocations of hours continued through 2022, well past the end of our study period.

publicized by the utilities themselves – we searched news articles for evidence of load shedding such news. We found evidence from newspaper articles of load shedding being allocated to high loss areas (and low loss areas being spare) in parts of India (Roy, 2013; Sen, 2022). Further, we found evidence that Eskom, the electricity utility in South Africa, has employed a form of load shedding targeted to areas with higher theft. Specifically, Eskom has implemented "load reduction" in which they shut down electricity supplies for a few hours a day in some areas in response to high electricity theft and illegal connections. The utility differentiates this load reduction from load shedding, which they claim occurs only due to insufficient generation capacity (Groenendaal, 2020).

A2 Distribution Infrastructure

The International Energy Agency (2020) expects that between 2020 and 2030, 16 million kilometers of existing electricity distribution lines need to be *replaced*, with approximately 60% of these replacement needs located in low and lower-middle income countries. This will require vast financial investments by distribution companies worldwide; and this does not even include the investments needed for *newly-constructed* distribution lines in settings that are being electrified for the first time in efforts to meet the Sustainable Development Goals.[38] Taken together, substantial investments in distribution infrastructure are expected in the near future. Further, distribution network investments are costly, not just in monetary terms but also in terms of time costs. Lower voltage distribution projects typically require 4-7 years to complete (International Energy Agency, 2022). Costs vary based on the quality and materials used in the components of the distribution network.

[38] Sustainable Development Goal 7 calls to "ensure access to affordable, reliable, sustainable and modern energy for all." As of 2020, 733 million people around the world still were without electricity (United Nations, 2022).

To better understand the different technology options available for use within distribution networks and and the path towards the cabling intervention studied in this paper, we conducted several types of literature searches. First, we reviewed the academic literature on ABCs, which is primarily from the field of electrical engineering, to understand the history of the ABCs technology, both in terms of the timing of development and the motivation for historical uses. Second, we looked to popular news coverage and project documents to understand the motivation for recent installation of ABCs in Pakistan. We report the results of our search in the following sub-sections.

A2.1 Low-cost Infrastructure

To invest in new or updated infrastructure, distribution companies need adequate revenue to cover those costs. Network revenues typically are generated through tariffs that are designed to incorporate the costs of grid investments (International Energy Agency, 2020). Inherently, there is a tension between pressure to keep electricity tariffs low and efforts to set tariffs sufficiently high in order to generate revenue to cover infrastructure investments. This tension is particularly felt in low and lower-middle income countries, where there are pressures to increase electricity access, but large proportions of the populations live in poverty. Efforts to keep down electricity tariffs in low-income settings means that the quality of infrastructure construction and service provision often diverges from that which is found in middle and high income settings.

Burying electricity lines underground is the best option, as it limits disruption from wind, storms and trees; however, it is also the most expensive. Of the aerial options, ABCs are more expensive than the open/bare lines frequently used in these settings. A distribution company must weigh the benefits of the different wire/cable options against their costs (Clapp et al., 1997). Analyses comparing the costs of replacing existing conductors with either new bare conductors, new covered conductors, or relocating the conductors underground, the costs were estimated to be 0.3, 0.43, and 3 million USD per mile, respectively (Southern California Edison, 2018). As a result, low voltage distribution lines in higher income countries are typically either buried underground or are comprised of covered conductors such as aerial bundled cables (ABCs), whereas in lower income countries bare wires were most often installed, until recently.

A2.2 Technical Background and Historical Use of ABCs

Starting in the early 1970s, electricity distribution companies began installing aerial insulated and covered wires and cables within their distribution systems to overcome problems with bare wires. Broadly-speaking, "covered conductor" is the term used to refer to conductors with "an internal semiconducting layer and external insulating UV resistant layers to provide incidental contact protection", and this covering differentiates the conductor from a bare wire conductor.[39] Aerial Bundled Cables (ABCs), one type of commonly used covered conductor, are twisted and tightly bundled insulated low voltage

[39]Other terms used for "covered conductors" include "insulated conductor" and "coated conductor" (Pacific Gas and Electric Company, 2021).

cables (Pacific Gas and Electric Company, 2021).[40] When introduced to electricity distribution systems in the late 1900s, ABCs were considered quite revolutionary; upon installation in Australia in the early 1980's, ABCs were hailed as "the biggest step forward in overhead distribution line practice in 50 years" (Williamson et al., 1989).

The earliest ABC installations are documented in high income countries, justified by the technology's ability to increase personal safety and make the distribution system resistant to external abrasion and puncture due to trees (Oliveira et al., 1996; Li, Su and Shen, 2010). For example, when the Electricity Supply Board serving the Republic of Ireland replaced their aging traditional open distribution wires with low voltage ABC lines in the late 1970s, they argued that ABCs led to fewer incidences of accidental electrical contact, improved continuity of service provision during storms, and reduced need for frequent tree trimming (Murray, 1995).

Since the 1980s, ABCs have become ubiquitous in many high income countries, particularly in Europe. La Salvia (2006) mapped ABC low voltage usage worldwide as of 2006; at that time, ABCs were pervasive in Europe and installed – albeit less extensively – in South America. For example, international energy giant, Enel Power, reported on its extensive introduction of ABCs back in 1993 (Gasparini et al., 1993) and, as of early 2000s, low voltage ABCs were France's largest installed distribution network (La Salvia, 2006). In the northeastern region of the United States, an estimated 80% of distribution lines are comprised of covered conductors, with the remaining 20% comprised of bare wires (Southern California Edison, 2018). Recently, covered conductors – including ABCs – have received much attention in California, as the state seeks to prevent future wildfires (Pacific Gas and Electric Company, 2021). Other high income countries with extensive installation of covered conductors include the United Kingdom, Finland, Sweden, South Korea and Japan.

Historically, there is less ABC installation in South Asia and Africa, with South Africa being a notable exception (La Salvia, 2006). However, the literature indicates that the justifications for ABC installation have shifted over time, leading to the technology spreading to additional countries.

A2.3 ABCs to Reduce Unbilled Consumption

The characteristics of ABCs that make them less prone to tree puncture also make them less susceptible to illegal tapping and electricity pilferage. Indeed, in recent publications, engineers argue that replacing basic aerial lines with ABCs is considered a "practical and effective" solution to reduce non-technical losses by (Abdollahi et al., 2020). This use of ABCs is particularly focused on settings where electricity theft is common, in low and lower middle income countries (La Salvia, 2006). The literature documents the installation of ABCs with the specific purpose of reducing theft, and non-technical losses more broadly, by utilities in countries such as Brazil, India, Iran, Mexico (La Salvia, 2006; Agarwal, Mukherjee and Barna, 2013; Abdollahi et al., 2020).

The potential of ABCs to help rectify the challenge of unbilled consumption is clearly

[40] Depending on the setting, ABCs refer to aerial bundled cables, aerial bunched cables, aerial bunch conductors, and aerial bundled conductors. We will use ABCs to refer to all of these.

described in a recent report on India (Regy et al., 2021). Theft, which occurs through meter tampering and illegal tapping into bare wires, is a major source of losses in India. Incurring high losses annually, distribution companies then have difficulty paying for investments in upgraded or new infrastructure or even for the electricity purchased from generation companies.

The Indian central government recommended that distribution companies upgrade their infrastructure in order to reduce losses, including the use of ABCs for high and low tension distribution lines to reduce illegal direct hooking (Regy et al., 2021). This recommendation is perhaps not surprising, given ABCs are believed to have contributed to reductions in transmission and distribution losses within India between 2003 and 2016, with installations documented in the states of Assam, Delhi, Gujarat, Jharkhand, Madhya Pradesh, Maharashtra, Punjab, and Uttarkand (PricewaterhouseCoopers Pvt. Ltd., 2016).

Recent research has shown that ABCs can reduce losses due to both technical inefficiencies and unbilled consumption. Abdollahi et al. (2020) conduct a simulation study to closely measure the effects of ABCs on both technical inefficiencies and unbilled consumption in Iran, where losses are high (18% of total energy input), like our setting, and 80% of those occur in the distribution system. Their study's key findings are pertinent to ours. First, before the installation of ABCs, the majority of total losses are due to unbilled consumption (1970.03 kW, or 70%), rather than technical inefficiencies (844.28 kW, or 30%). Second, unbilled consumption was essentially eliminated after the installation of the ABCs, providing strong evidence to support the claim that ABCs make illegal tapping impossible. Third, together, these findings mean that of the ABC-induced reduction in total losses, 92% came from the elimination of unbilled consumption.

A2.4 Cable Installation in Pakistan

In its 2022 State of the Industry Report, Pakistan's regulator recommended that the country's electricity distribution companies install ABCs in order to reduce losses (NEPRA, 2022*a*). However, theft and ABCs were already major points of discussion for Pakistan's electricity sector. Unbilled consumption and potential ways to mitigate it featured prominently in the country's news. Below we provide highlights of news stories from Pakistan covering ABCs.

- The Express Tribune. September 07, 2015. "Against tampering: Locals to have theft-resistant electricity cables." Article discussed how the Peshawar Electric Supply Company (PESCO) was replacing old wires with ABCs in an effort to reduce electricity theft. https://tribune.com.pk/story/951944/against-tampering-locals-to-have-theft-resistant-electricity-cables

- Such TV. November 24, 2018. "New system being introduced to stop power theft: Omar Ayub." In a television interview, Pakistan's Minister of Energy explained that ABC installation would help control electricity theft and announce plans for an Asian Development Bank funded effort to install ABCs within the distribution network of IESCO, PESCO, and LESCO. https://www.suchtv.pk/pakistan/general/item/77702-new-system-being-introduced-to-stop-power-theft-omar-ayub.html

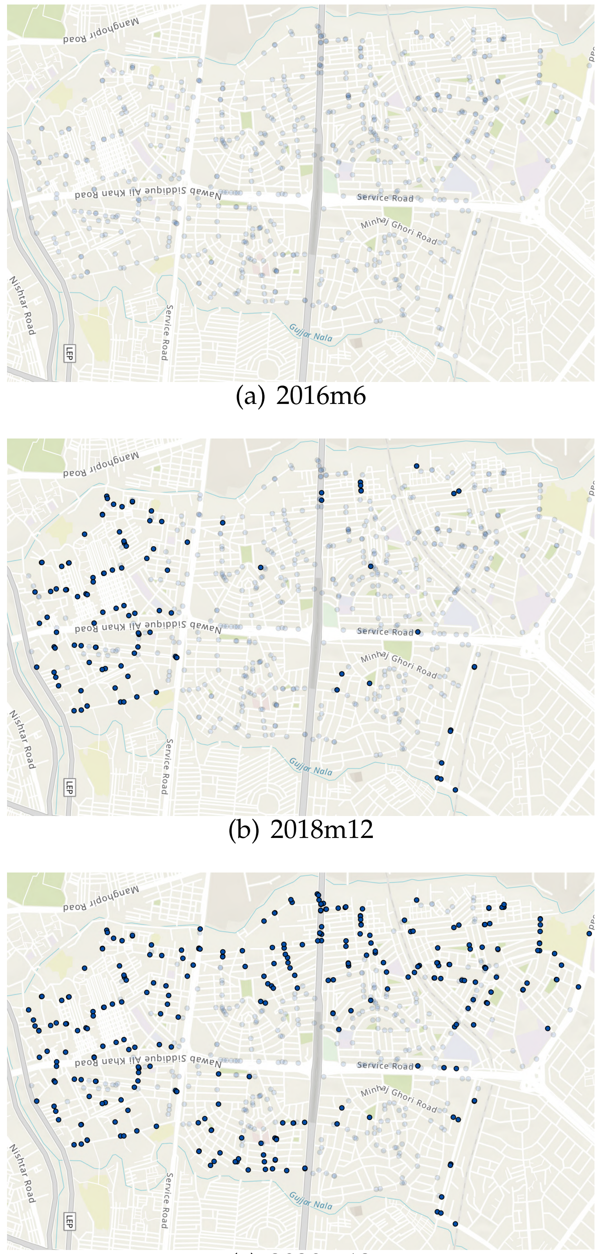
- Pakistan Today. July 27, 2020. "Segmented load-shedding in line with National Power Policy: K-Electric." The article described Karachi Electric's efforts to reduce electricity theft through the installation of ABCs. https://profit.pakistantoday.com.pk /2020/07/27/segmented-load-shedding-in-line-with-national-power-policy-k-electric/

- Business Recorder. November 30, 2020. "K-Electric to invest $1.5 billion in energy infrastructure." Article reports that the utility already invested 55 billion rupees into its distribution network in FY 2020, converting to ABCs and "significantly reducing transmission and distribution losses, and load shedding." https://www.brecorder.com/news/40036286

- The Daily Times. December 19, 2020. "K-Electric requests consumers' understanding as it conducts annual preventive maintenance." Article reported that installation of ABCs is a regular part of Karachi Electric's work to upgrade the network and reduce illegal kundas in Karachi. https://dailytimes.com.pk/703407/k-electric-requests-consumers-understanding-as-it-conducts-annual-preventive-maintenance/

- The News International. November 23, 2022. "KE says transmission, distribution losses reduced to 15pc in FY22." Article reported on discussion of Karachi Electric's Chief Financial Officer and the company's efforts "to enhance its infrastructure and continue efforts to reduce distribution losses by rolling out aerial bundled cables on its network." https://www.thenews.com.pk/print/1012680-ke-says-transmission-distribution-losses-reduced-to-15pc-in-fy22

B Maps



(a) 2016m6

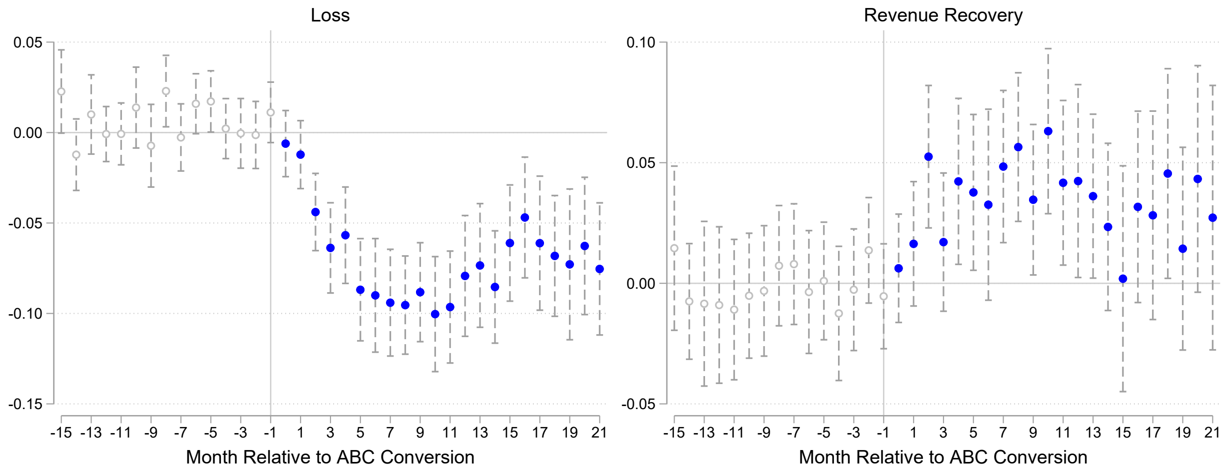
(b) 2018m12

(c) 2020m12

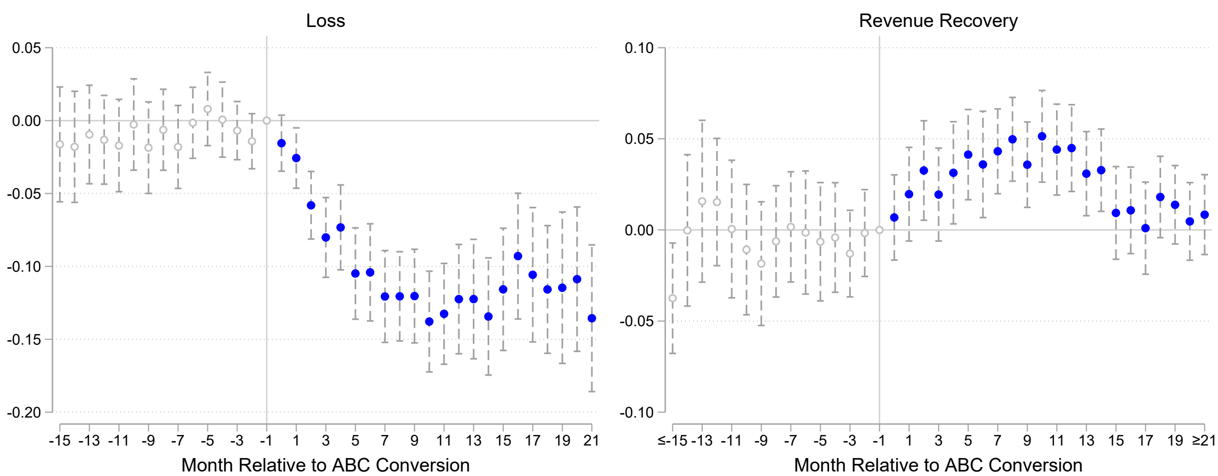
Figure B1: Example of Theft-Resistant Cable Installation at Transformers

Notes: The figures show the location of transformers in one of the IBCs with high losses. Light-colored circles indicate transformers without ABCs, and darker-colored circles indicate transformers that have been converted to ABCs.

C Additional Figures and Tables



(a) Adjusted Following Callaway and Sant'Anna (2021)



(b) Adjusted Following Sun and Abraham (2021)

Figure C1: Dynamic Impacts on Losses and Revenue Recovery – Alternative Estimators

Notes: We use alternative estimators to address concerns on the staggered DID setting. Panel (a) plots the event study estimates following the approach suggested by Callaway and Sant'Anna (2021). Panel (b) plots the event study estimates following the approach suggested by Sun and Abraham (2021). The figure shows the coefficients and their 95% confidence intervals. Data are at the feeder level on a monthly basis. Regressions include IBC-by-month and feeder fixed effects. Standard errors are clustered at the feeder level.

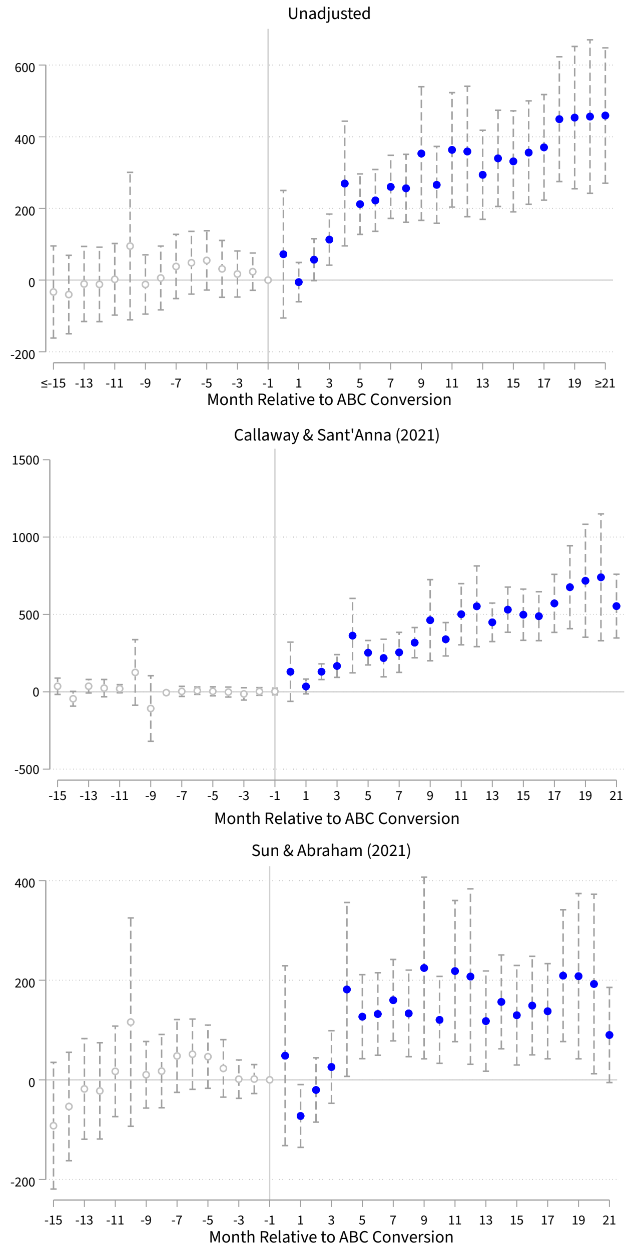


Figure C2: Dynamic Impacts on the Number of Consumers

Notes: The figure shows the coefficients and their 95% confidence intervals from event-study regressions estimating the impact of ABCs on the number of consumers measured in inverse hyperbolic sines. The top panel presents estimates from unadjusted event-study model. The middle panel presents estimates following the approach suggested by Callaway and Sant'Anna (2021). The bottom panel plots the estimates following the approach suggested by Sun and Abraham (2021). Data are at the feeder-line level. Regressions include IBC-by-month and feeder-line fixed effects. Standard errors are clustered at the feeder-line level.

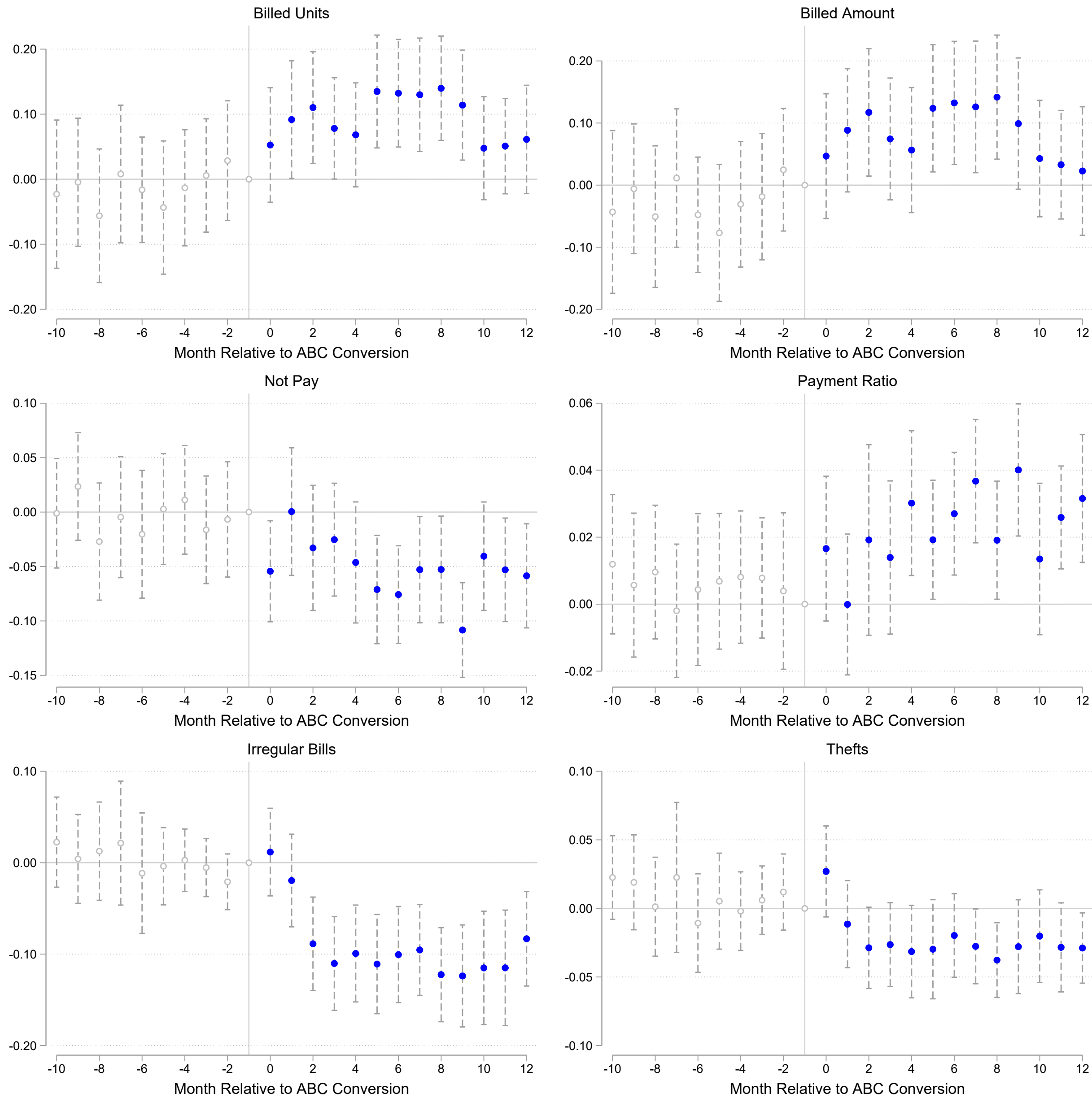


Figure C3: Dynamic Impacts on Customer Behavior

Notes: The figure plots coefficients and their 95% confidence intervals from the event-study estimates of the ABC effect. We use the standard event-study framework without any adjustments. The outcome variables include billed electricity units (in inverse hyperbolic sine), billed electricity amount (in inverse hyperbolic sine), an indicator for whether the customer does not pay electricity bills on time, the proportion of payment relative to the total due to KE (payment ratio), an indicator for whether there are irregular bills in that month, and an indicator for whether there is theft in that month. All regressions include customer, month, and transformer-by-month-of-year fixed effects. Standard errors are clustered at the transformer level.

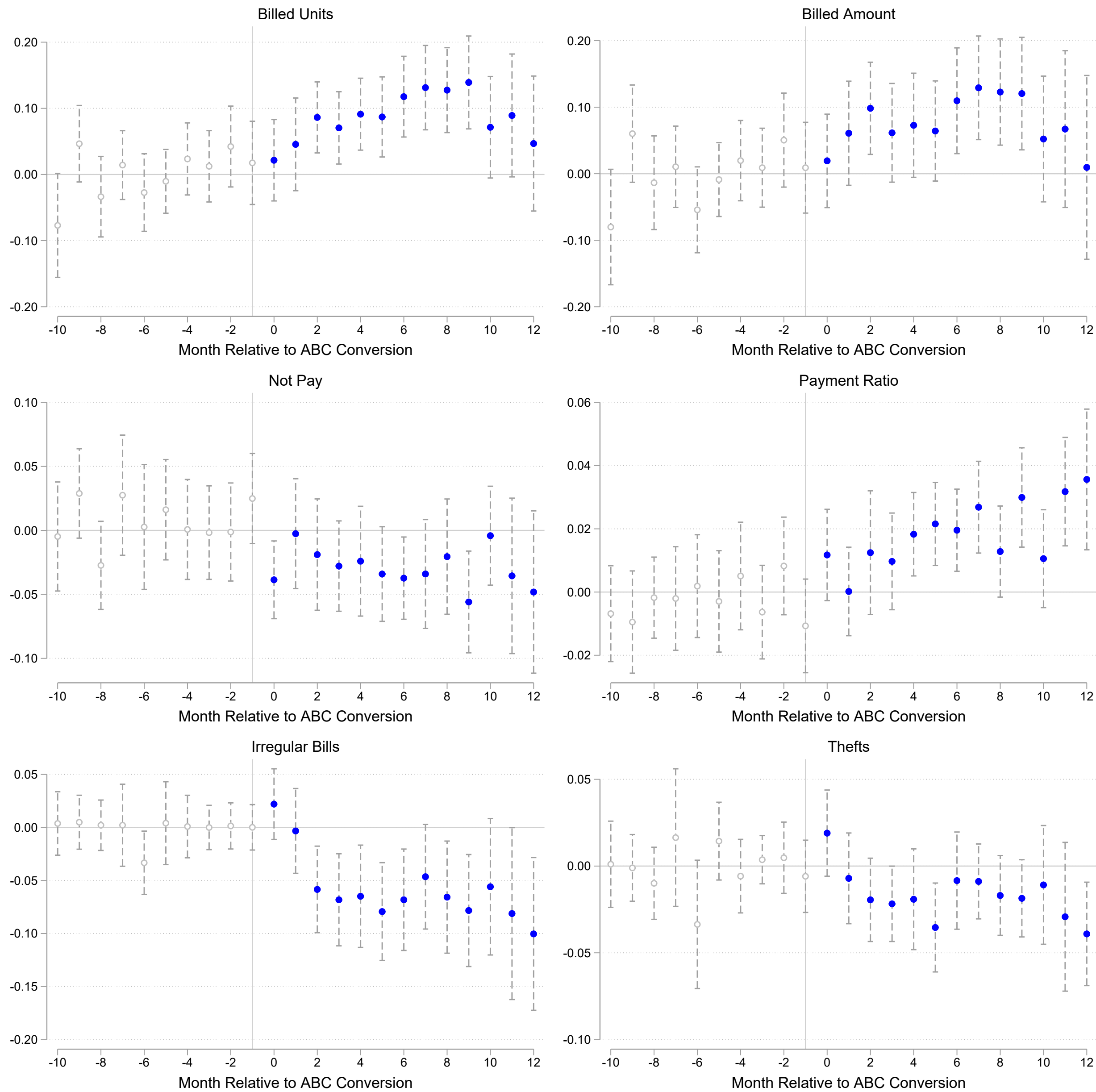


Figure C4: Dynamic Impacts on Customer Behavior – Callaway and Sant'Anna (2021)

Notes: The figure plots coefficients and their 95% confidence intervals from the event-study estimates of the ABC effect. We use the estimator proposed by Callaway and Sant'Anna (2021) to address the concerns on staggered DID setting. The outcome variables include billed electricity units (in inverse hyperbolic sine), billed electricity amount (in inverse hyperbolic sine), an indicator for whether the customer does not pay electricity bills on time, the proportion of payment relative to the total due to KE (payment ratio), an indicator for whether there are irregular bills in that month, and an indicator for whether there are thefts in that month. All regressions include customer, month, and transformer-by-month-of-year fixed effects. Standard errors are clustered at the transformer level.

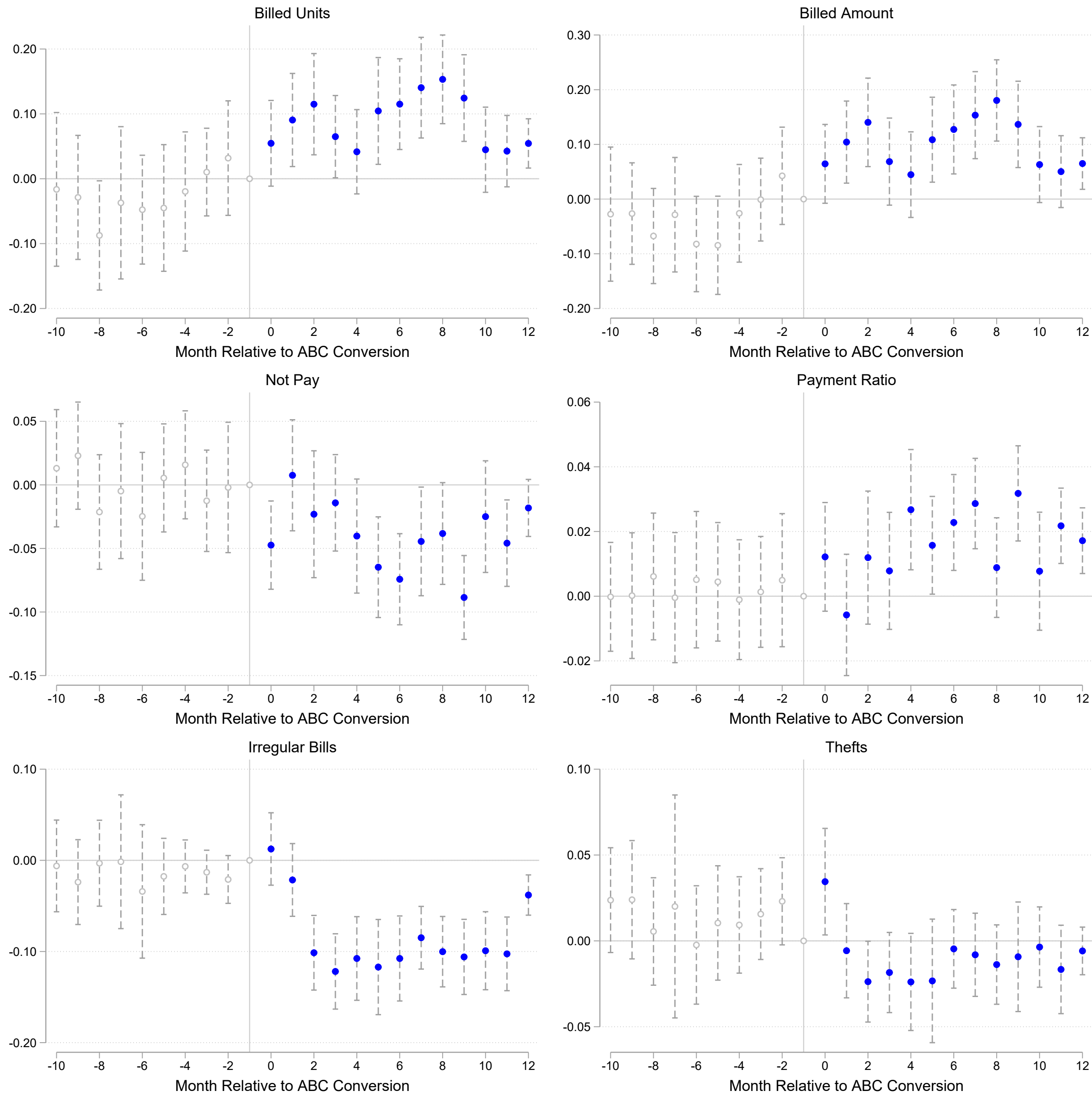


Figure C5: Dynamic Impacts on Customer Behavior – Sun and Abraham (2021)

Notes: The figure plots coefficients and their 95% confidence intervals from the event-study estimates of the ABC effect. We use the estimator proposed by Sun and Abraham (2021) to address the concerns on staggered DID setting. The outcome variables include billed electricity units (in inverse hyperbolic sine), billed electricity amount (in inverse hyperbolic sine), an indicator for whether the customer does not pay electricity bills on time, the proportion of payment relative to the total due to KE (payment ratio), an indicator for whether there are irregular bills in that month, and an indicator for whether there are thefts in that month. All regressions include customer, month, and transformer-by-month-of-year fixed effects. Standard errors are clustered at the transformer level.

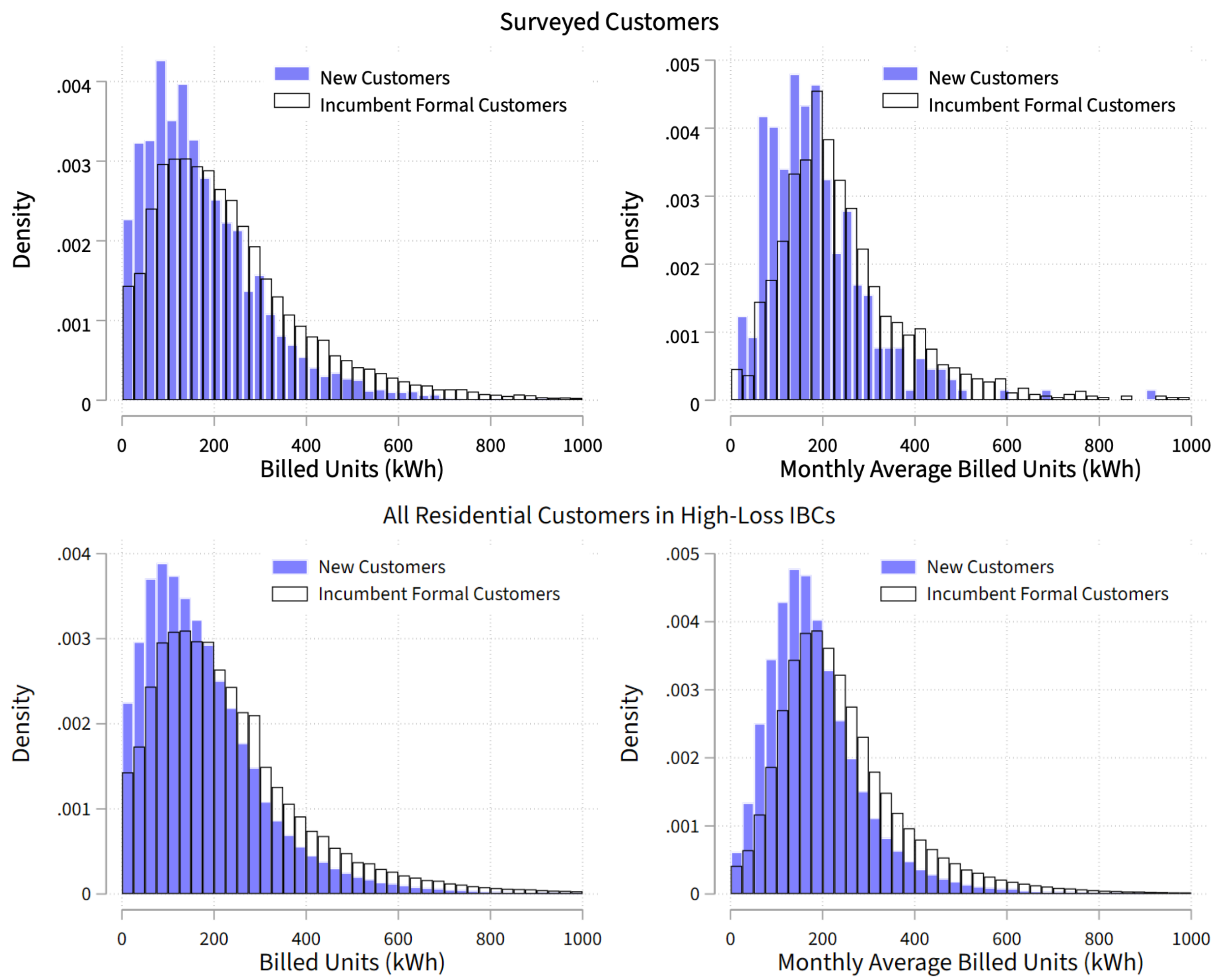


Figure C6: Distribution of Billed Units by Customer Type

Notes: Data are at the customer-month level. The top panels focus on the surveyed customers in our study sample. The bottom panel uses all the residential customers in high-loss IBCs. The left panels plot the histogram of monthly billed units. The right panels plot the histogram of each customer's average monthly billed units over the sample period. New customers are defined as those who contracted with KE within 6 months of the ABC conversion at the corresponding transformers. The remaining customers are defined as incumbent formal customers. When plotting these figures, we restrict to transformers that ultimately have ABC conversions during our sample and focus on the post-ABC period.

Table C1: Summary Statistics of Feeder-Line Characteristics

	Never ABC (1)	ABC Treated (2)	Early ABC (3)	Late ABC (4)	Treated vs Never (2) - (1)	Early vs Never (3) - (1)	Late vs Never (4) - (1)	Late vs Early (4) - (3)
Quantity Sent Out (GWh)	0.871	1.124	1.052	1.164	0.274***	0.226***	0.299***	0.053
	(0.661)	(0.519)	(0.505)	(0.522)	(0.038)	(0.043)	(0.051)	(0.063)
Quantity Billed (GWh)	0.676	0.657	0.636	0.669	-0.013	-0.016	-0.010	0.009
	(0.532)	(0.319)	(0.386)	(0.274)	(0.025)	(0.040)	(0.029)	(0.051)
Loss	0.218	0.387	0.377	0.392	0.181***	0.176***	0.183***	0.006
	(0.176)	(0.169)	(0.169)	(0.170)	(0.011)	(0.013)	(0.014)	(0.019)
Gross Billing (1000 K)	12.209	9.359	8.605	9.762	-1.731***	-1.773***	-1.679***	0.774
	(13.010)	(4.488)	(3.886)	(4.731)	(0.353)	(0.376)	(0.462)	(0.544)
Net Credit (1000 K)	10.362	5.957	5.857	6.011	-3.864***	-3.418***	-4.069***	-0.300
	(11.500)	(3.707)	(2.978)	(4.044)	(0.340)	(0.317)	(0.446)	(0.441)
RR	0.842	0.650	0.694	0.626	-0.224***	-0.186***	-0.244***	-0.077**
	(0.208)	(0.241)	(0.189)	(0.262)	(0.021)	(0.018)	(0.029)	(0.034)
# Residential Customers	1,016.799	2,131.007	1,953.410	2,225.317	1,141.139***	979.298***	1,222.346***	170.626
	(1,276.399)	(953.663)	(907.021)	(964.578)	(87.221)	(93.069)	(117.469)	(136.531)
# Total Customers	1,272.772	2,504.729	2,334.234	2,595.268	1,255.414***	1,099.871***	1,333.457***	158.008
	(1,464.534)	(1,016.470)	(1,010.206)	(1,008.419)	(93.767)	(104.769)	(124.769)	(147.739)
Share of Residential Customers	0.577	0.839	0.829	0.845	0.260***	0.246***	0.267***	0.011
	(0.382)	(0.108)	(0.120)	(0.101)	(0.013)	(0.015)	(0.016)	(0.017)
# Transformers	16.735	18.255	19.296	17.688	1.507	2.562**	0.953	-1.686
	(14.306)	(9.694)	(11.707)	(8.346)	(0.929)	(1.269)	(1.170)	(1.609)
# Feeder Lines	1509	194	124	70				

Notes: Data are at the feeder-line level. To calculate these baseline statistics, we restrict the sample to the pre-ABC period for each treated feeder line. When calculating the means, we absorb month fixed effects to capture seasonality. There are 1,888 feeder lines throughout the study period. For ease of interpretation, we exclude from all columns the 185 feeder lines that had ABCs installed in or before January 2018, as they were were in the midst of undergoing treatment during the data period. Column (1) shows feeder lines that never get ABC conversion during our whole sample period. Column (2) shows feeder lines that have ABC conversion after January 2018. Column (3) shows feeder lines that have ABC conversion between February 2018 and June 2019. Column (4) shows feeder lines that had ABC conversion slightly later, after June 2019. In the first four columns, the values in parentheses are standard deviations. In the last four columns, the values in parentheses are standard errors, clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C2: Summary Statistics of General Household Characteristics

Variable	Mean	SD	Min	Max
Household Characteristics				
Number of Adults	4.34	2.84	1	46
Number of Children	2.66	2.35	0	27
Total Number of People	7.00	4.06	1	47
Years in the Neighborhood	22.37	18.53	1	80
% Housing Owners	0.79	0.41	0	1
% Housing Renters	0.21	0.41	0	1
House Characteristics				
Number of Rooms	2.71	1.33	1	12
% Pucca	0.76	0.42	0	1
% Katcha	0.19	0.39	0	1
% Both Pucca and Katcha	0.05	0.21	0	1
Connectivity				
% Cell Phone	0.60	0.49	0	1
% Mobile Internet	0.60	0.49	0	1
Expenditures				
Total Monthly Expenditures	33,426.02	25,095.02	0	418,300
Expenditure on Food	18,543.54	13,283.91	0	300,000
Expenditure on Electricity	5,001.27	8,851.94	0	250,000
Expenditure on Water	983.88	1,939.43	0	40,000
Expenditure on House Rent	1,759.76	4,427.53	0	90,000
Expenditure on Other Rent	257.70	1,259.82	0	22,000
Expenditure on Other Utilities	250.19	878.24	0	25,000
Expenditure on Durables	80.57	1,450.02	0	50,000
Expenditure on Transportation	2,221.53	4,502.02	0	90,000
Expenditure on Other Recurring	175.48	1,097.79	0	30,000
Expenditure on Healthcare	2,747.38	11,354.45	0	350,000
Expenditure on Education	2,557.88	6,811.91	0	200,000
Asset Ownership and Financial Accounts				
% Own Vehicles	0.04	0.19	0	1
% Own Motorcycles	0.59	0.49	0	1
% Own Land	0.05	0.22	0	1
% Financial Account	0.32	0.47	0	1

Notes: Statistics are calculated from our household survey conducted in 2021. Pucca houses are made of solid materials, such as brick and cement. Katcha houses are made of more temporary materials.

Table C3: Summary of Electricity-Related Household Characteristics and Reports

Variable	Mean	SD	Min	Max
Electricity Connection Details				
Years with KE Connection	20.98	19.04	1	80
% Households Paying KE for Electricity	0.87	0.33	0	1
% Households Paying Other Entity for Electricity	0.09	0.28	0	1
% Meter Installed	0.96	0.19	0	1
% Meter Calculating Peak Consumption	0.19	0.39	0	1
% Households Checking Meter Regularly	0.06	0.23	0	1
% Share Meter with Other Households	0.01	0.11	0	1
Summer Monthly Electricity Expense (PKR)	5,635.48	6,988.37	500	200,000
Winter Monthly Electricity Expense (PKR)	3,885.55	7,812.55	300	250,000
Lighting Sources				
% Use Candle	0.12	0.32	0	1
% Use Lantern	0.01	0.09	0	1
% Use Kerosene Oil	0.01	0.11	0	1
% Use Battery Light	0.34	0.47	0	1
% Use Solar Powered Light	0.14	0.35	0	1
% Use Generator	0.06	0.23	0	1
% Use Mobile Light/Torch	0.06	0.24	0	1
Electricity Service Quality				
Summer Outage/Load Shedding Hours per Day	7.63	2.72	0	24
Winter Outage/Load Shedding Hours per Day	5.62	3.08	0	24
% Experience Appliance Damages	0.27	0.45	0	1
% Use Device to Prevent Voltage Fluctuation	0.38	0.49	0	1
% Report Electricity Shortage	0.46	0.50	0	1
% Report Voltage Fluctuation	0.12	0.33	0	1
% Report Unplanned Load Shedding	0.73	0.45	0	1
% Report High Expense Electricity	0.72	0.45	0	1
% Report Frequent Billing Errors	0.28	0.45	0	1
Appliance Ownership				
% Own Refrigerator	0.75	0.43	0	1
% Own Microwave Oven	0.01	0.10	0	1
% Own Washing Machine	0.72	0.45	0	1
% Own Air Conditioner	0.03	0.16	0	1
% Own TV	0.48	0.50	0	1
% Own Electric Water Pump	0.69	0.46	0	1
Total Number of Appliances	7.41	3.01	0	37
Light Bulb Types				
% Use Incandescent	0.01	0.07	0	1
% Use CFLs	0.26	0.44	0	1
% Use LEDs	0.84	0.36	0	1

Notes: Statistics are calculated from our household survey conducted in 2021.

Table C4: Effect of Theft-Resistant Cables on Losses and Revenue Recovery – Alternative Clustering

	Loss	Revenue Recovery
Coefficient Estimate	-0.082	0.052
S.E. Clustered by:		
Feeder	(0.009)***	(0.009)***
IBC	(0.017)***	(0.013)***
Feeder & Calendar Month	(0.013)***	(0.010)***
IBC & Calendar Month	(0.018)***	(0.013)***
Observations	47,575	37,353
Feeder FE	✓	✓
IBC-Month FE	✓	✓

Notes: We report the coefficient estimates using the model corresponding to Columns 1 and 2 in Table 1 but with alternative clustering standard errors. The first row replicates the coefficient estimates of the ABC dummy. In the following rows, we present the standard errors clustered by (i) feeder-lines; (ii) IBC regions; (iii) feeder-lines and calendar month; and (iv) IBC region and calendar month. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C5: Nonlinear Effects of Theft-Resistant Cables

	Monthly		Quarterly	
	Loss	Revenue Recovery	Loss	Revenue Recovery
	(1)	(2)	(3)	(4)
ABC Ratio	-0.159^{***}	0.176^{***}	-0.130^{***}	0.185^{***}
	(0.030)	(0.039)	(0.035)	(0.041)
ABC Ratio^2	-0.019	-0.092^{**}	-0.048	-0.086^{**}
	(0.032)	(0.042)	(0.037)	(0.043)
Control Mean	0.260	0.792	0.243	0.813
Observations	47,575	37,353	17,626	14,664
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓		
IBC-Quarter FE			✓	✓

Notes: Data are at the feeder-line level. ABC ratio is defined as the number of transformers with ABCs installed divided by the number of total transformers in a feeder-line. All regressions include feeder-line and IBC-by-month/quarter fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C6: Heterogeneous Effects by High/Low-Loss feeder-lines

	Monthly		Quarterly	
	Loss	Revenue Recovery	Loss	Revenue Recovery
	(1)	(2)	(3)	(4)
ABC	-0.024^{*}	-0.033^{***}	-0.006	-0.024^{***}
	(0.014)	(0.010)	(0.014)	(0.009)
ABC $\times$ Medium Loss	-0.061^{***}		-0.057^{***}	
	(0.016)		(0.016)	
ABC $\times$ High Loss	-0.135^{***}		-0.126^{***}	
	(0.030)		(0.029)	
ABC $\times$ Medium Revenue Recovery		0.098^{***}		0.073^{***}
		(0.013)		(0.014)
ABC $\times$ Low Revenue Recovery		0.182^{***}		0.153^{***}
		(0.022)		(0.023)
Control Mean	0.260	0.792	0.243	0.813
Observations	43,041	23,461	16,495	9,635
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓		
IBC-Quarter FE			✓	✓

Notes: Data are at the feeder-line level. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. We classify the initial losses or revenue recovery rate (the monthly average losses or revenue recovery rate between January 2018 and June 2018) into three categories by percentile: low, medium, and high. The ABC indicator is then interacted with binary indicators for whether the feeder-line falls into certain loss or revenue recovery categories. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C7: Robustness Checks: Effects of Theft-Resistant Cables on Losses and Revenue Recovery

	Loss		Revenue Recovery	
	Coef.	S.E.	Coef.	S.E.
A. Only Keep feeder-lines Neighboring Early Adopters				
Drop Early Converted feeder-lines	-0.113***	(0.015)	0.052***	(0.017)
Drop Early Converted or High-Loss feeder-lines	-0.134***	(0.019)	0.084***	(0.024)
B. Only Keep feeder-lines Distant from Each Other				
>100m Distance	-0.081***	(0.009)	0.053***	(0.009)
>300m Distance	-0.088***	(0.010)	0.053***	(0.010)
>500m Distance	-0.095***	(0.017)	0.046***	(0.015)
C. Control ABC Status of Neighboring feeder-line Areas				
<100m Distance	-0.077***	(0.009)	0.053***	(0.009)
<300m Distance	-0.082***	(0.009)	0.053***	(0.009)
<500m Distance	-0.081***	(0.009)	0.052***	(0.009)
D. Alternative Estimators				
Doubly-Robust Estimator	-0.062***	(0.011)	0.029**	(0.012)
E. Restricted Sample				
Restrict to >6 Months from Initial ABC Conversion	-0.120***	(0.012)	0.059***	(0.012)
F. Add Additional Fixed Effects				
Feeder + IBC-by-Loss-Category-by-Month	-0.066***	(0.008)	0.048***	(0.009)
Feeder-by-Calendar-Month + IBC-by-Month	-0.092***	(0.010)	0.053***	(0.010)

Notes: Data are at the feeder-line level. The coefficient estimate in each cell is from a separate regression. In Panel A, we address the concern of time-varying feeder-level changes, leveraging the utility company's "ring-fencing" strategy. For each feeder-line area, we identify all its neighboring feeder-line areas within the 1km buffer. Then, we drop the feeder-line area if it has the earliest ABC conversion among them. The remaining feeder-lines are likely to be followers of ABC conversion according to the "ring-fencing" strategy. In addition to dropping the earliest converters, we also drop the high-loss feeder-lines as an additional check. In Panel B, we only keep the feeder-lines with at least 100 m, 300 m, or 500 m distance from their nearest neighbors. In Panel C, we add controls for the ABC status of the neighboring feeder-line areas located within 100 m, 300 m, or 500 m distance. In Panel D, we report the aggregated average treatment effect on the treated for all the timing groups across all periods using the doubly-robust DID estimator proposed by Callaway and Sant'Anna (2021). In Panel E, for the feeder lines that ultimately have ABC conversion, we restrict their post-ABC period to at least more than 6 months from the initial ABC conversion. In Panel F, we use combinations of more flexible fixed effects to capture potential confounding factors, including (i) feeder and IBC-by-loss-category-by-month fixed effects; (ii) feeder-by-calendar-month and IBC-by-month fixed effects. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C8: Robustness Checks: CSR Camps

VARIABLES	Loss		Revenue Recovery	
	(1)	(2)	(3)	(4)
Panel A: Exclude Feeder Line Areas with CSR Camps				
ABC	-0.076***	-0.088***	0.064***	0.057***
	(0.012)	(0.014)	(0.013)	(0.015)
Buffer	300m	500m	300m	500m
Observations	23,975	19,763	18,233	14,808
Panel B: Heterogeneous Effect by CSR Camping Areas				
ABC	-0.083***	-0.096***	0.064***	0.046***
	(0.012)	(0.014)	(0.012)	(0.014)
ABC $\times$ CSR300	0.003		-0.025	
	(0.017)		(0.017)	
ABC $\times$ CSR500		0.022		0.009
		(0.018)		(0.017)
Observations	47,575	47,575	37,353	37,353

Notes: Data are at the feeder-line level. Regression use data from KE on the location of all corporate social responsibility (CSR) programs during 2018-2021, including business facilitation camps and health camps. In Panel A, we exclude the feeder line areas if they have a transformer that is located within 300 or 500 meters of a KE CSR camp location. In Panel B, CSR300 and CSR500 are indicators for whether the feeder line has a transformer that is located within 300 or 500 meters of a CSR camp location, respectively. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C9: Robustness Checks: Old Meter Replacements

	Restrict to Pre-OMR Period		Restrict to Non-OMR Feeder Lines		Control OMR			
Dep. Var.	Loss	RR	Loss	RR	Loss	RR	Loss	RR
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ABC	-0.068***	0.046***	-0.068***	0.063***	-0.080***	0.051***	-0.075***	0.055***
	(0.011)	(0.011)	(0.015)	(0.015)	(0.009)	(0.009)	(0.009)	(0.010)
OMR					-0.011	0.010	0.013	0.026*
					(0.009)	(0.010)	(0.013)	(0.014)
ABC × OMR							-0.031**	-0.022
							(0.015)	(0.015)
Observations	44,956	35,142	40,990	31,606	47,575	37,353	47,575	37,353
#Feeder	1,824	1,797	1,636	1,610	1,852	1,827	1,852	1,827
Feeder FE	✓	✓	✓	✓	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓	✓	✓	✓	✓

Notes: Data are at the feeder-line level. ABC is a binary indicator that equals 1 when the feeder line has transformers with ABCs installed, and equals zero otherwise. OMR is a binary indicator that equals 1 for a feeder line after old meter replacements are initiated for any transformer, and equals zero otherwise. In columns (1) and (2), for feeder lines that ultimately have old meter replacements, we restrict the data to the period prior to the first meter replacement record. In columns (3) and (4), we exclude the feeder lines that ever have transformers with old meter replacements. All regressions include feeder line and IBC-by-month fixed effects. Standard errors are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C10: The Effects of Old Meter Replacements

	Restrict to Pre-ABC Period		Restrict to Post-ABC Period	
Dep. Var.	Loss (1)	RR (2)	Loss (3)	RR (4)
OMR	-0.023 (0.015)	0.018 (0.019)	-0.010 (0.010)	0.016 (0.010)
Observations	38,202	29,660	9,279	7,602
#Feeder	1,656	1,624	368	368
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓

Notes: Data are at the feeder-line level. OMR is a binary indicator that equals 1 for a feeder line after old meter replacements are initiated for any transformer, and equals zero otherwise. In columns (1) and (2), for feeder lines that ultimately have ABC conversion during our sample, we restrict the data to the pre-ABC period. In columns (3) and (4), we restrict the data to feeder lines that ever have ABC conversion and to their post-ABC period. All regressions include feeder line and IBC-by-month fixed effects. Standard errors are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C11: Robustness Checks: Project Sarbulandi

VARIABLES	Loss (1)	Revenue Recovery (2)
A. Exclude Phase-1 Sarbulandi IBCs	-0.073***	0.028**
	(0.011)	(0.012)
B. Exclude the Post Period for Phase-1 Sarbulandi IBCs	-0.071***	0.045***
	(0.009)	(0.009)
C. Restrict to the Period Before November 2019	-0.065***	0.060***
	(0.010)	(0.010)
D. Only Keep Phase-2 Sarbulandi IBCs	-0.082***	0.028**
	(0.012)	(0.012)
E. Only Keep Phase-1 Sarbulandi IBCs	-0.089***	0.075***
	(0.013)	(0.014)

Notes: Data are at the feeder-line level. Each cell reports the coefficient estimate of the ABC indicator and the corresponding standard error from a separate regression. Panel A excludes feeder line areas that belong to Phase-1 Sarbulandi IBCs. Panel B excludes the post-Sarbulandi period (i.e., post November 2019) for Phase-1 IBCs. Panel C restrics the sample to the period before November 2019 when the project Sarbulandi hasn't started yet. Panel D only includes feeder lines that belong to Phase-2 Sarbulandi IBCs. Panel E only includes feeder lines that belong to Phase-1 Sarbulandi IBCs. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C12: Effect of Theft-resistant Cables on Consumer Numbers - Alternative Specifications

VARIABLES	Total (1)	Agricultural (2)	Bulk (3)	Commercial (4)	Industry (5)	Residential (6)
A. Log Measure						
ABC	0.066***	-0.002	-0.003	-0.018	-0.010	0.065**
	(0.022)	(0.015)	(0.005)	(0.028)	(0.030)	(0.026)
B. Raw Level Winsorized at the 99th Percentile						
ABC	169.041***	-0.041	-0.005	2.333	-0.484	166.851***
	(40.694)	(0.079)	(0.007)	(5.568)	(0.745)	(37.175)
C. Inverse Hyperbolic Sine						
ABC	0.065***	−0.002	−0.004	−0.023	−0.009	0.064**
	(0.022)	(0.019)	(0.006)	(0.029)	(0.035)	(0.028)
D. Log Measure						
ABC Ratio	0.140***	0.004	-0.006	-0.043	-0.018	0.161***
	(0.032)	(0.007)	(0.006)	(0.043)	(0.045)	(0.040)
E. Raw Level Winsorized at the 99th Percentile						
ABC Ratio	444.990***	-0.054	-0.009	4.269	-1.325	439.582***
	(57.608)	(0.080)	(0.009)	(7.389)	(1.151)	(52.419)
F. Inverse Hyperbolic Sine						
ABC Ratio	0.138***	0.005	−0.008	−0.053	−0.015	0.159***
	(0.033)	(0.009)	(0.008)	(0.047)	(0.052)	(0.043)
Outcome Mean	1582.96	1.24	0.09	263.41	11.71	1306.51
Observations	67,602	67,602	67,602	67,602	67,602	67,602

Notes: Data are at the feeder-line level. The outcome variables are the number of customers belonging to a specific category. Panel A and D use log measures, i.e., the logarithm of one plus the outcome variable. Panel B and E use raw levels winsorized at the 99th percentile. Panel C and F use inverse hyperbolic sines. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. ABC Ratio is defined as the number of transformers with ABCs installed divided by the total number of transformers in a feeder-line. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C13: Effect of Theft-Resistant Cables on Load Shedding – Inverse Hyperbolic Sine

	IHS(Average Hours of Load Shedding Per Day)			
	Whole Sample		High-Loss IBCs	
	(1)	(2)	(3)	(4)
ABC	-0.107***		-0.111***	
	(0.029)		(0.028)	
ABC Ratio		-0.264***		-0.279***
		(0.038)		(0.037)
Outcome Mean	4.068	4.068	5.994	5.994
Observations	34,997	34,997	12,298	12,298
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓

Notes: Data are at the feeder-line level on a monthly basis. The outcome variable is average hours of load shedding per day in a month (measured in inverse hyperbolic sine). ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of transformers with ABCs installed divided by the number of total transformers in a feeder-line. All regressions include feeder and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C14: Effect of Theft-Resistant Cables on Consumer Complaints – Alternative Specifications

Variables	All	Bill Complaints	Service Requests	Technical Complaints
	(1)	(2)	(3)	(4)
A. Log Measure, Total Number				
ABC	-0.088***	0.200***	-0.102***	-0.232***
	(0.023)	(0.027)	(0.037)	(0.030)
B. Raw Levels Winsorized at the 99th Percentile, Total Number				
ABC	-23.080***	2.518***	4.073**	-29.104***
	(3.671)	(0.335)	(1.904)	(3.094)
C. Inverse Hyperbolic Sine, Total Number				
ABC	−0.079***	0.223***	−0.126***	−0.238***
	(0.023)	(0.031)	(0.041)	(0.032)
D. Log Measure, Per-Capita Number				
ABC	-0.014***	0.001***	0.002**	-0.017***
	(0.002)	(0.000)	(0.001)	(0.002)
E. Raw Levels Winsorized at the 99th Percentile, Per-Capita Number				
ABC	-0.016***	0.001***	0.002**	-0.019***
	(0.002)	(0.000)	(0.001)	(0.002)
F. Inverse Hyperbolic Sine, Per-Capita Number				
ABC	−0.016***	0.001***	0.002*	−0.018***
	(0.002)	(0.000)	(0.001)	(0.002)
Observations	71,918	71,918	71,918	71,918

Notes: Data are at the feeder-line level. The outcome variable is the number of consumer complaints, including all types of complaints, bill complaints, and service requests. Panel A and D use log measures, i.e., the logarithm of one plus the outcome variable. Panel B and E use raw levels winsorized at the 99th percentile. Panel C and F use inverse hyperbolic sines. In Panel A, B and C, we use the total number of complaints and add consumer number as a control variable. In Panel D, E, and F, we use per-consumer measures, defined as the number of complaints divided by the number of consumers covered by a feeder-line. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table C15: Quantile Regression Analysis – The Effect of ABCs on Billed Units

Dep. Var.: Billed Units (kWh)	10th (1)	25th (2)	50th (3)	75th (4)	90th (5)
A. Add Customer FE					
ABC	15.864***	14.753***	13.468***	11.351***	8.887***
	(0.765)	(0.724)	(1.023)	(1.802)	(2.813)
cons	104.173***	156.473***	217.034***	316.730***	432.827***
	(0.719)	(0.483)	(1.101)	(1.557)	(1.934)
B. No Customer FE					
ABC	6.670***	5.469***	3.978***	1.817	-1.167
	(0.678)	(0.633)	(1.042)	(1.882)	(3.126)
cons	72.524***	128.853***	198.803***	300.226***	440.216***
	(0.563)	(0.401)	(0.839)	(1.378)	(2.001)
Month FE	✓	✓	✓	✓	✓
Transformer-Month-of-Year FE	✓	✓	✓	✓	✓

Notes: Data are at the customer-by-month level. The sample includes all residential customers in high-loss IBCs. The outcome variable is billed unit (in kWh). We report the results from quantile regressions where we estimate the impacts of ABC on percentiles of billed units. Panel A adds customer fixed effects while Panel B does not. All columns include month fixed effects and transformer-by-month-of-year fixed effects. Standard errors in parentheses are clustered at the transformer level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

D Utility Cost-Benefit Calculations

To put the magnitude of the benefits from ABCs into perspective, we perform cost-benefit calculations from the utility's perspective.

D1 Costs of ABCs (Theft-resistant Cables) to the Utility

We create four cost scenarios based on cost numbers provided by KE. These scenarios, presented in Table D1, provide us with a range of the overall costs of ABC installation. The costs that can potentially be included in our calculations are: the costs of purchasing the ABC materials themselves, the labor costs for replacing the old bare wires with the ABCs, the cost of purchasing – in addition to the ABC materials – new meters to replace those old meters installed on the premises of the customer, and the additional labor cost of replacing those old meters.

We include the costs of ABC materials alone in Scenario 1, whereas Scenario 2 captures both the ABCs materials and the labor (per transformer) required to install it. To include only material costs (and not labor) is not unrealistic, as distribution system wires must regularly be replaced at the end of their lifespan. Even in the absence of the upgrade to ABCs, we can assume that technical work on the distribution system would still be required and even bare wire need to be regularly replaced – perhaps with even greater frequency than ABCs. Therefore, labor expenses are not necessarily specific to this infrastructure upgrade and could be omitted from the calculations of costs.

Table D1: Costs to the Utility for ABC Conversion, per Customer

Scenario	Costs Included in Scenario	Cost per Customer (PKR)	(USD)
1	ABC materials alone	16,389	109.3
2	ABC materials + labor	20,487	136.6
3	ABC materials + old meter replacement	24,916	166.1
4	ABC materials + old meter replacement + labor	33,630	224.2

Notes: Calculations based on cost data from KE. Conversions from PKR to USD are based on the exchange rate during the period of ABC installation studied, which was approximately 1 USD = 150 PKR.

In some cases – but not all – KE replaced the old meters with new meters at the time when ABC conversion occurred. These new meters are the same technology as the old ones that they replaced, just newer (i.e., they are not a more advanced technology, such as prepaid meters or smart meters). The old meters were replaced if they were either damaged and not properly functioning or – because the ABC wires replace all the bare wires in the distribution system, even those leading directly to the house – it was more efficient for the utility to replace the meter at the same time that the ABC was installed. For these reasons, we create two additional cost scenarios, one in which the old meters are replaced at the time of the ABC conversion (Scenario 3) and one that additionally includes the associated labor costs (Scenario 4). Given KE did not replace all old meters during our study period, we know that Scenarios 3 and 4 are higher than expected for the per customer cost of the ABC installation.

We assume the costs of ABCs are all upfront and therefore borne in year 0. Further, to put these costs into units comparable to the benefits, we divide the costs per transformer by the average number of consumers per transformer, with an average of 200 consumers per transformer in our dataset. The resulting costs by scenario are in Table D1, in both rupees and dollars.

D2 Benefits to the Utility

We estimate the benefits of ABC installation to the electricity utility using the change in customer payments to KE following the conversion to ABCs. We do so using the results from Table 4 on the increase in the monetary billed amount, which is 331,708,768 PKR per month or 3,980,505,216 PKR per year. We convert this into a per-consumer benefit to the utility, by dividing these total benefits per year by the number of consumers in high-loss areas (694,743 consumers in high-loss areas). This provides us with an estimated benefit to the utility of 5,729 PKR per consumer per year.

We must make assumptions regarding the expected lifespan of the ABC technology when installed in Karachi. Globally, ABCs have an expected lifespan between 15 to 20 years. However, based on conversations with the electricity utility, we understand that the ABCs may function for a shorter period (approximately ten years) when installed in Pakistan, due to the local conditions. For this reason, we calculate the benefits for multiple expected lifespans, ranging from 10 to 20 years.

We assume that the annual benefits are constant over these expected duration periods. Benefits could potentially decrease over time; however, we argue that the numbers here provide a conservative estimate of the benefits to the utility, as we are not including other known benefits, such as the reduction in payments to the utility's field workers to disconnect kundas.

We calculate the benefits using a range of discount rates: 8%, 10%, and 12%. We determined these to be reasonable discount rate based on the Kibor Rates reported by the

State Bank of Pakistan (www.sbp.org.pk) for this time period. Results are in Table D2, reported in rupees and dollars in Panels A and B, respectively.

Table D2: Utility's Discounted Benefits per Customer from ABC Conversion

Variations in discount rates	Assumed ABC Lifespan 20 years	15 years	10 years
Panel A: In PKR			
8%	56252.7	49041.2	38445.2
10%	48778.2	43578.8	35205.1
12%	42795.9	39022.6	32372.8
Panel B: In USD			
8%	375.0	326.9	256.3
10%	325.2	290.5	234.7
12%	285.3	260.2	215.8

Notes: Calculations assume constant benefits over the assumed lifespan. Conversions to USD are based on the exchange rate during the period of ABC installation studied, which was approximately 1 USD = 150 PKR. Discount rates are based on Kibor Rates documented by the State Bank of Pakistan for this time period.

These expected benefits are calculated using the estimated effects of KE's cable conversion, which they targeted to high loss feeder lines. We cannot expect that the installation of these theft-resistant cables on low loss feeders would have the same effects. As such, a hypothetical systemwide conversion would not have the same benefits across all of the utility;s territory.

D3 Comparing Costs and Benefits of Theft-Resistant Cables, by Expected Lifespans and Discount Rates

We compare the four cost scenarios presented in Table D1 with the benefits presented in Table D2 for all four expected ABC lifespans and the three different discount rate. These net present value per customer calculations are presented in rupees and dollars in Tables D3 and D4, respectively.

Results in Panel C present perhaps the most realistic estimates of the net present value of ABC installation, given the expected 10-year lifespan – is what KE expects for ABCs installed in Karachi. In all but the most conservative scenario (i.e., 12% discount rate with the scenario of ABC costs that we know is higher than those actually incurred on average), the expected benefits outweigh the costs. These NPV calculations are likely to further understate the true tradeoff for the utility, given our benefits calculations only include the additional billed value collected by the utility.

Table D3: Net Present Value per Consumer (PKR): Costs versus Benefits of Cable Conversion

	Cost Scenarios (PKR)			
Variations in lifespans and discount rates	1	2	3	4
Panel A: 20-year lifespan				
8%	39863.5	35766.2	31337.1	22622.2
10%	32388.9	28291.6	23862.5	15147.6
12%	26406.7	22309.4	17880.3	9165.3
Panel B: 15-year lifespan				
8%	32652.0	28554.7	24125.6	15410.7
10%	27189.5	23092.2	18663.1	9948.2
12%	22633.4	18536.1	14106.9	5392.0
Panel C: 10-year lifespan				
8%	22055.9	17958.6	13529.5	4814.6
10%	18815.8	14718.5	10289.4	1574.5
12%	15983.5	11886.2	7457.1	-1257.8

Notes: All values are in PKR per customer. Discount rates are based on Kibor Rates documented by the State Bank of Pakistan for this time period.

Table D4: Net Present Value per Consumer (USD): Costs versus Benefits of Cable Conversion

	Cost Scenarios (USD)			
Discount Rate for Benefits	1	2	3	4
Panel A: 20-year lifespan				
8%	265.8	238.4	208.9	150.8
10%	215.9	188.6	159.1	101.0
12%	176.0	148.7	119.2	61.1
Panel B: 15-year lifespan				
8%	217.7	190.4	160.8	102.7
10%	181.3	153.9	124.4	66.3
12%	150.9	123.6	94.0	35.9
Panel C: 10-year lifespan				
8%	147.0	119.7	90.2	32.1
10%	125.4	98.1	68.6	10.5
12%	106.6	79.2	49.7	-8.4

Notes: All values are in USD per customer. Conversions to USD are based on the exchange rate during the period of ABC installation studied, which was approximately 1 USD = 150 PKR. Discount rates are based on Kibor Rates documented by the State Bank of Pakistan for this time period.

E Theft Reduction and Consumer Surplus

E1 A Model of Cables' Impacts on Consumers

At baseline, excluding non-payers from electricity consumption is difficult for the electricity utility. The introduction of ABCs makes such exclusion more feasible. In this section, we provide a simple model to conceptualize how consumer surplus may change with the introduction of ABCs.

E1.1 The Setup

We consider a case in which there are two types of residential electricity consumers that acquire electricity via the grid, F (formal consumers) and K (kunda users). Formal consumers are those that registered with the the utility and are served by a formal connection to the electrical grid. Formal consumers receive a bill from KE for electricity services consumed, as captured by the electricity meter readings. Kunda users are not served by a formal KE connection. Instead, they connect to the electrical grid through an informal line, called a kunda. The kunda user pays a fixed monthly fee to the kunda provider for their consumption, which is unmetered. The utility does not receive any of the fee from the kunda user.[41] Both formal consumers and kunda users can reside in the same neighborhoods. All consumers within a neighborhood are served by the same feeder-line and therefore are exposed to common feeder-line-level shocks, such as electricity rationing (also known as load shedding).

Distribution losses are the difference between the quantity of electricity sent to a feeder-line and the quantity billed to formal consumers, divided by the amount sent out. High rates of losses translate into budgetary constraints for the utility. There is heterogeneity across feeder-lines in their composition of the two consumer types, resulting in differences in rates of distribution losses as well. In general, high-loss feeder-lines have a high proportion of kunda users, whereas lower-loss feeder-lines have a higher proportion of formal consumers.

In addition to above-mentioned budget constraints, the utility operates under supply constraints that necessitate electricity rationing. Given both the supply and budget constraints, KE allocates a larger quantity of electricity to the feeder-lines from which it will

[41] For ease of exposition, we simplify the scenario to these two consumer types. Although a formal consumer could, on occasion, manipulate their meter or also use a kunda, so as not to pay the full cost of their electricity services consumed, we note that mathematically it would be equivalent to ”split” such a consumer into two distinct consumers, one with a ”formal demand” and one with a ”kunda demand.” Intuitively, this is similar to the construction of a demand curve with different willingness to pay for additional units of a product under the law of diminishing marginal utility.

recoup a higher rate of payment (i.e., the feeder-lines with lower losses). To operationalize this, KE assigns feeder-lines to load shedding categories. feeder-lines with greater losses have rationing set higher, at q_H (i.e., more hours of load shedding and fewer hours of electricity provision). feeder-lines with lower losses have rationing set at a lower level, q_L (i.e., fewer hours of load shedding and more hours of electricity provision).

If ABCs increase the feasibility of excluding kunda users, then a feeder-line's losses would decrease after ABC installation. If rationing is tied to losses, then a decrease in a feeder-line's losses may result in less rationing, with a shift from q_H to q_L.

We focus on the partial equilibrium here. If focusing on the general equilibrium, we would extend this to consider how a reduction in losses would alleviate the utility's budget constraints, thereby permitting it to make investments to relax supply constraints.

E1.2 Introduction of ABCs

ABCs have the potential to make electricity excludable, by limiting the feasibility of kundas and thereby shifting their users to formal connections. If the ABCs reduce the incidence of kundas, then losses would be lower and potentially alleviate budget constraints. The utility would be better off.

The effects of ABCs on consumer surplus, however, are less obvious. In the subsections that follow, we describe ABCs' effects on the surplus of formal consumers and kunda users to elucidate how some consumers might be better off, while others are worse off. In doing so, we illustrate several points. First, the effects on consumer surplus differ across the two consumer types, formal consumers and kunda users. Second, the formal consumers are no worse off than they were prior to ABC installation and potentially are better off if electricity rationing on their feeder-line decreases. Third, the change in consumer surplus for kunda users is ambiguous and depends on several factors, such as the magnitude of the kunda fee, the extent to which rationing changes after ABC installation, and whether rationing was binding before ABC installation.

E1.3 Formal Consumers: Change in Consumer Surplus

We illustrate the potential impacts of ABCs on the surplus of formal consumers in Figure E1. We depict an individual demand curve of a representative formal consumer in two scenarios: (i) one in which rationing is non-binding, as shown on the left-hand side, and (ii) one in which electricity rationing is binding, as shown on the right-hand side. In both scenarios the formal consumers' consumption is measured by the electricity meter, and they are charged the price per kWh of electricity, P_F, as set by the government regulator.

Before ABC Installation. When electricity rationing is non-binding, formal consumers would consume up to quantity q_F, where P_F intersects with the demand curve. Consumer surplus is the area lightly shaded above P_F. If this is a high-loss feeder-line, then KE rations electricity at q_H, making that the maximum quantity any individual on the feeder-line may consume. This does not affect consumer surplus when $q_F < q_H$ (the non-binding scenario). However, if rationing is binding at q_H, then the surplus of the formal consumer is constrained, as depicted by the lightly shaded area in the graph on the right-hand side.

After ABC Installation. After installation of ABCs, the price remains constant at P_F for formal consumers. Consumption could remain constant, if rationing is not binding. In these cases, we do not expect the formal consumers' surplus to change. If rationing was binding at q_H, however, and then is relaxed from q_H to q_L, we expect the quantity consumed to increase.

This shift in rationing from q_H to q_L is depicted in Figure E1. The consumer surplus after ABC installation is depicted by the thin crossed pattern. The area in which the thin crossed pattern does not overlap with the light shading is the change in consumer surplus that results from the change in load shedding after ABC installation. Taking both scenarios together, we expect that the $\Delta CS \geq 0$ for these formal consumers following the introduction of ABCs. In other words, formal consumers are no worse off with the introduction of ABCs.

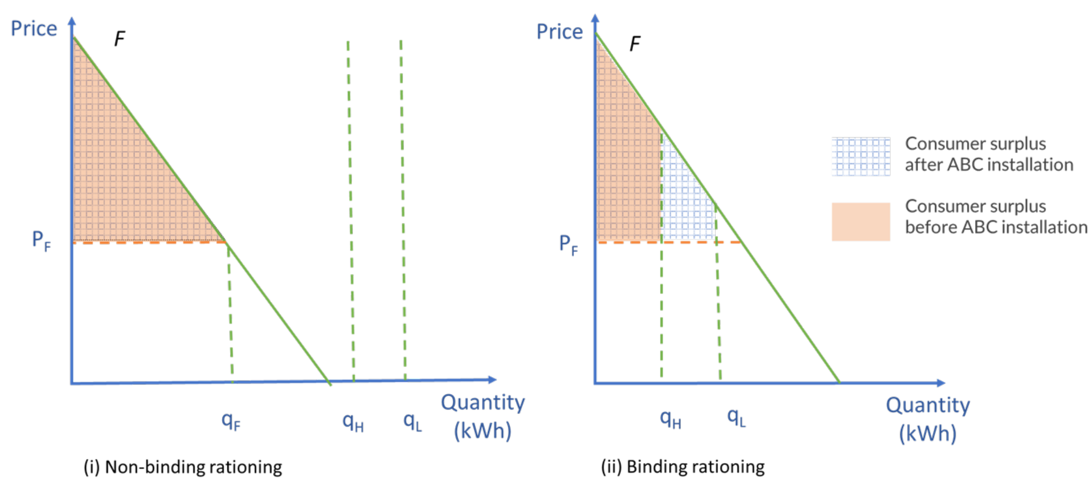


Figure E1: Consumer Surplus of Formal Consumers

Notes: The graphs depict individual demand curves and two levels of electricity rationing, q_H and q_L. Rationing is non-binding on the left-hand side (i) and binding on the right-hand side (ii). Price is constant both before and after ABC installation, as consumers were always paying the tariff price set by the regulator, P_F.

E1.4 Kunda Users: Change in Consumer Surplus

Here we conceptualize the change in consumer surplus for kunda users following the installation of ABCs, illustrating that both the direction and the magnitude of the change in surplus are ambiguous and depend on at least three factors: the magnitude of the kunda fee, the extent to which rationing is binding, and the magnitude of the change in rationing.

We present graphs depicting kunda user surplus in Figure E2. As in the case of the formal users, there can be electricity rationing, which may or may not be binding. Again, it is helpful to depict both scenarios: (i) one in which rationing is non-binding, as shown in the graph on the left-hand side, and (ii) one in which electricity rationing is binding, as shown in the graph on the right-hand side.

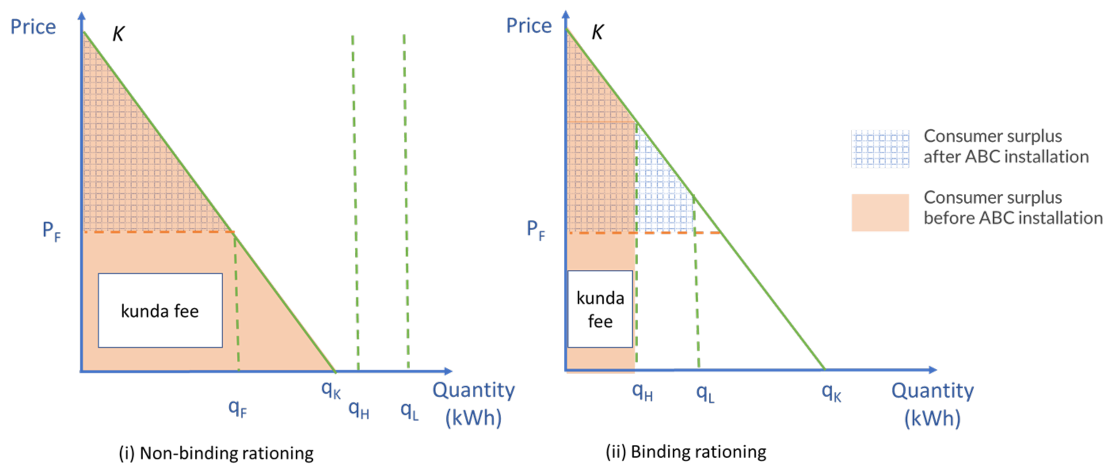


Figure E2: Consumer Surplus of Kunda Users

Notes: The graphs depict individual demand curves, with two levels of electricity rationing, q_H and q_L. Rationing is non-binding on the left-hand side (i) and binding on the right-hand side (ii). Before the installation of ABCs, this consumer is a kunda user and pays only a fixed monthly amount (the kunda fee) to the kunda provider. After the installation of ABCs, kundas are no longer a viable channel to access electricity. After ABC installation, if the consumer wants to use electricity services from the grid, they must pay the regulator-set tariff price, P_F.

Before ABC Installation. Kunda users connect to the electrical grid through informal connections. These consumers are not paying the state-determined tariff price, P_F. Instead, they pay a fixed monthly fee to the entity providing the connection, a kunda fee, which is represented as a white block in both graphs. This fixed fee means that there is a zero marginal cost for additional units consumed. If electricity rationing is not binding ($q_K < q_H$), the kunda user would consume to quantity q_K. If rationing is binding at q_H, then consumption will be limited at that quantity.

In both scenarios, the consumer surplus is the lightly shaded area below the individual demand curve minus the amount of the monthly kunda fee, as depicted by the unshaded block. In both scenarios – binding and non-binding – before ABC installation, the consumer surplus will depend on the magnitude of the kunda fee set by informal providers. From focus groups of households in high-loss areas of Karachi during fall 2021, we understand kunda fees are prevalent in this setting and have information on their magnitude as well. We assume that the kunda fee is less than the expected cost of consuming electricity services via a formal connection; otherwise kunda users would prefer a formal connection.

After ABC Installation. Once ABCs are installed, kundas are no longer feasible. The kunda user must shift to paying the state-determined tariff price, P_F, if they want to consume electricity services.

When rationing is non-binding (as on the left), the change from a fixed fee to the state tariff, P_F, will result in a decrease in consumption from q_K to q_F. The consumer surplus is now just the area above P_F, as shaded by the thin crossed pattern. With rationing non-binding, both q_K and q_F are less than q_H. If rationing decreases and provision of electricity services increases to q_L, these individuals do not gain any surplus. Thus, in this scenario the kunda users are unambiguously worse off following ABC installation. However, this change in consumer surplus may not be as large as expected, depending on the magnitude of the kunda fee previously paid.

When rationing is binding (as on the right), the direction of the change in consumer surplus due to ABC installation is ambiguous. Kunda users could have consumed only to q_H, the quantity set by rationing. These individuals are forced to pay the formal tariff rate and lose the consumer surplus represented by the area below P_f and up to q_H, minus the kunda fee. Again, the magnitude of this change in consumer surplus might not be as large as expected and depends on the amount previously paid as a kunda fee. Additionally, if a reduction in losses means that rationing is relaxed from q_H to q_L, then these individuals can increase their consumption to that quantity. As a result, their surplus may increase. The relative magnitudes of the two changes – the surplus decrease resulting from the price change and the surplus increase resulting from additional hours of electricity provision – will determine to what extent these kunda users are worse off or better off than before ABC installation.

E2 Consumer Surplus Calculation

We now present some exploratory results quantifying the welfare impacts of ABC installation by measuring the costs to the subsidized consumers and the change in government expenditures. We restrict our analysis to high-loss IBCs and feeder-lines that ultimately had ABCs installed.

ABCs make illegal electricity connections or theft more difficult. As is shown in previous sections, there is an increase in consumers' billed amount and payment ratio after the ABC installation. Hence, we characterize the ABC installation as an informal tax on consumers for their electricity usage. The change in billed amount and payment ratio can be approximated by an average price increase faced by consumers in feeder-lines with ABCs installed. Therefore, for tractability, we consider the tax as a per-unit tax.

To measure the change in consumer surplus, we estimate price elasticities of electricity demand. We leverage the monthly feeder-level data on electricity sent out, bill payment, and the number of customers to conduct the estimation. For each feeder-line, we calculate the average electricity consumption per consumer (y_{it}) as the total consumption divided by the average number of customers in the period after ABC installation.[42]

The average electricity price (p_{it}) faced by consumers is measured as the total expenditure on electricity usage divided by the total consumption. Consumers' expenditures on electricity usage include the amount they pay to KE (for legal connections).[43]

With the calculated average electricity consumption and average electricity price, we estimate the price elasticity of demand using the two-stage least squares approach. For feeder-line i in IBC region j in month t, the first- and second-stage regressions are:

$$\begin{aligned} \ln(p_{ijt}) &= \gamma \text{ABC}_{it} + \alpha_i + \delta_{jt} + \varepsilon_{ijt} \\ \ln(y_{ijt}) &= \beta \ln(\hat{p}_{ijt}) + \phi_i + \kappa_{jt} + u_{ijt}. \end{aligned}$$

In the above equations, γ captures the change in electricity price after the ABC installation, and β captures the price elasticity of electricity demand. With these parameters, we can calculate the change in consumer surplus as a result of the average price increase induced by the ABC installation.

ABC installation satisfies the exclusion restriction under the assumption that it does not affect average consumption except through its effect on average prices. However,

[42] The total electricity consumption at each feeder-line is measured by the electricity sent out $\times$ $(1-$technical loss rate). Here, we assume an 8% technical loss rate based on NEPRA's estimation. Implicitly, we assume a balance between the electricity supply and demand.

[43] As kunda pricing is considered a lump-sum transfer, we ignore kunda payments for the purposes of calculating the average price.

given our empirical results that ABCs lead to formalization (new customers joining) and also reduced rationing (due to reduction in load shedding), the aggregated feeder level quantities consumed will be affected via channels other than the increase in price. Thus, our calculations should be interpreted as exploratory calculations.

The changes in consumer surplus calculated above contain within them the lump-sum transfers made to kunda operators before ABC installation. To account for this, we estimate the amount of transfer using results from our household survey. According to the household survey, we assume the proportion of households using kundas is 10% and test different kunda price assumptions ranging from zero to 3,500 PKR per month. Then, we calculate the total payment for kunda usage by multiplying the kunda price by the number of households using kundas in each feeder-line. We assume consumers no longer pay for a kunda after ABC installation since illegal connections are terminated.

The change in government subsidies is calculated by multiplying the change in electricity consumption per customer with the average subsidy rate (i.e., 4.7 PKR according to KE) and the total number of customers.

Table E1 presents the results from these calculations under a range of assumptions for kunda prices. We see that consumer surplus decreases following the introduction of ABCs in all scenarios presented; however, the extent to which it decreases is highly dependent on kunda prices. For the range of plausible kunda prices, calculations indicate that consumer surplus reductions are between 2.21 and 4.55 USD per month. Further, although we find that in aggregate, consumer surplus falls, we note that service quality improvements are not accounted for in our surplus calculations.

Table E1: Effect of Theft-Resistant Cables on Consumer Surplus and Government Subsidies

Kunda Fee (1)	ΔCS per Consumer (2)	ΔCS Total (3)	ΔKunda Revenue (4)	ΔSubsidy (5)
0	−682	−473,548,704	0	−133,894,840
750	−607	−421,442,915	−52,105,772	−133,894,840
1,500	−532	−369,337,143	−104,211,544	−133,894,840
2,000	−482	−334,599,962	−138,948,725	−133,894,840
2,500	−432	−299,862,781	−173,685,906	−133,894,840
3,500	−332	−230,388,418	−243,160,269	−133,894,840

Notes: All values are in Pakistani rupees per month. The exchange rate during this period was approximately 1 USD = 150 PKR. Kunda prices are based on prices reported in our focus groups in fall 2021. The change in total consumer surplus (ΔCS) is calculated by multiplying the per-customer change (column 2) by the number of customers in high-loss areas following the ABC intervention (694,743 customers). ΔSubsidy is measured by the change in government subsidies for electricity. Details for the calculation are described in Section E2.

F Implications for Climate Change Mitigation

Ex ante, the implications of the theft-resistant cable installation for electricity generation and, therefore CO_2 emissions, are not obvious. If anything, our results suggest that emissions may increase as a result of infrastructure upgrades: the cables led to an increase in both the total number of utility customers and billed units (kWh) per customer, which together suggest an increase in electricity supplied and therefore electricity generated. In a setting such as Pakistan, where 62% of electricity generation is via fossil fuels (NEPRA, 2021), an absolute increase in electricity generation likely means an increase in CO_2 emissions.

F1 Estimating Reductions in Emissions

In this section, we explore the implications of the infrastructure upgrade for climate change mitigation through a multi-step process. First, we estimate the impacts of theft-resistant cables on a proxy for electricity generation. Then, we calculate the marginal changes in CO_2 emissions per kWh change in electricity generated. Third, using the results of the prior two steps, we perform back-of-the-envelope calculations to estimate the cables' influence on CO_2 emissions. Lastly, to provide some perspective, we compare these estimates to the CO_2 emissions from KE's annual generation.

For the first step, given that generation occurs at a higher level than the intervention, we use the quantity of electricity "sent out" (kWh) to a feeder-line per month (i.e., the quantity delivered to a feeder-line) as a proxy for generation per feeder-line.[44] To estimate the impact of the cables on electricity generation, we run regressions akin to those described in Equation 1, but with the quantity sent out as the outcome variable. Results in Table F7 show that theft-resistant cables led to a decrease in generation of 97,213.3 kWh per feeder-line per month (column 1). Using the inverse hyperbolic sine transformation of the quantity sent out, the intervention led to a 10.2% decrease in generation per feeder-line per month (column 2). These results indicate that the cables reduced the total electricity delivered and, therefore, the quantity generated.

To translate these generation reductions per month into avoided CO_2 emissions, we perform calculations of the estimated reduction in CO_2 emissions per kWh reduction of electricity generated, specific to Pakistan's generation mix. Details of these calculations

[44] Electricity sent out includes billed consumption, unbilled consumption, and technical losses. A reduction in technical losses can be considered a pure welfare gain as CO_2 emissions are averted but consumption is not reduced. However, a reduction in billed or unbilled consumption might have welfare consequences for consumers, which we are unable to capture in this calculation.

are in Appendix F3. Broadly speaking, we create a mix of fuels that would most likely be used to respond to changes in demand. This ”responsive mix” consists mostly of generation attributed to fossil fuels, as these technologically allow for relatively easier changes in production, compared with other sources. Our calculations indicate that the reduction in CO_2 per kWh reduction of electricity services consumed is 0.76 kg CO_2/kWh for our responsive mix.

Note that the above estimate is one of many alternatives. If we instead assume that marginal production takes place solely through natural gas (the least carbon intensive of Pakistan's fossil fuel generation mix) or Residual Fuel Oil (the most carbon intensive of the country's fossil fuel generation mix), our estimates change to 0.46 kg CO_2/kWh and 1.06 kg CO_2/kWh, respectively. Our responsive mix then is a conservative estimate, between both bounds, though we provide estimates using all three.

After calculating the change in CO_2 emissions per change in electricity generated by generation fuel type, we compare those calculations to Pakistan's annual CO_2 emissions to put those numbers in perspective. Results are in Table F8. In column 1, we present the result of multiplying each of these estimated changes in CO_2 per kWh change in generation by fuel type times the estimated reduction in generation: 97,213.3 kWh per feeder-line per month (from column 1 of Table F7). This provides us with a range of estimated reductions in CO_2 emissions per year per feeder-line, by fuel source of the marginal generator. We aggregate these numbers to all high-loss feeders (column 3) and compare them with the estimated CO_2 emissions from KE's annual generation (column 4). This reduction in CO_2 emissions is non-trivial, equal to roughly 1.67% to 4.26% of KE's annual emissions due to generation.

F2 Comparing Theft-Resistant Cables with Other Interventions

To provide a sense of magnitude for these calculations, we compare the theft-resistant cables' reductions in billed electricity consumption with the feasible reductions from other technologies. To do so, we convert the theft-resistant cables' feeder-line-level reductions into residential consumer-level reductions. From our regressions, we know that the cables reduced the quantity sent out by 97,213.3 kWh per feeder-line per month. We divide that by the average number of residential consumers per feeder-line (1,685), which provides a cable-induced reduction in electricity consumption of 57.7 kWh per residential customer per month.

We perform back-of-the-envelope calculations for the electricity savings that would occur if a household replaced three incandescent light bulbs with more efficient LED light bulbs. We perform these calculations based on Carranza and Meeks (2021), which reports estimated reductions in electricity consumption due to a randomized energy efficient light bulb intervention in Kyrgyzstan. First, we calculate the power reduction (kW) per household from making this switch to LEDs.[45] We then use that estimated reduction to calculate the expected reduction in billed electricity (kWh) per month (Appendix Table F10). Calculations by season place the per-household kWh reduction due to switching three incandescent light bulbs to LEDs at between 24.3 and 44.55 kWh per month, which is just below the 57.7 kWh per month of the theft-resistant cable-induced reduction calculated per consumer. Therefore, the reduction from theft-resistant cables is equivalent to that of shifting to more efficient lighting.

F3 Calculations: Reductions in CO_2 Emissions

In this section, we detail the steps involved in calculations pertaining to CO_2 emissions and the impacts of ABCs on them. First, we calculate the CO_2 emissions produced for all electricity generated and delivered to the service area covered by KE. Second, we estimate the reduction in CO_2 per kWh reduction of electricity services consumed, in order to estimate the reduction in CO_2 emissions resulting from the installation of ABCs. Lastly, we use these two calculations together to compare the CO_2 emissions reductions from ABCs with the overall emissions from electricity purchased for the KE territory.

These calculations are conducted using information specific to Pakistan, from NEPRA's 2021 Annual State of the Industry Report (NEPRA, 2021).

F3.1 CO_2 Emissions for Electricity Purchased by Karachi Electric

We first calculate the CO_2 emissions for all units purchased for KE's service territory. NEPRA's report provides information on KE's system generation, as well as the purchases KE makes from the Central Power Purchasing Agency (CPPA-G). As shown in Table F1, the generation mix differs across the two sources.

In FY 2020-21, KE procured a total of 19,486 GWh. This consisted of electricity generated within the KE system (13,116 GWh), as well as outside purchases from CPPA-G (6,370 GWh) (NEPRA, 2021).

We calculate the average emissions intensity by generation fuel type. We assume a plant efficiency and apply an emissions factor to estimate the kg of CO_2 per MWh.

[45] We assume households would replace a 100 W incandescent bulb with a 100 W equivalent LED bulb. Actual wattage listed for LEDs is typically 10 W for a 100 W equivalent bulb. Therefore for each incandescent bulb replaced by an LED, there is a reduction of 90 W (100 W − 10 W). If the household has three light bulbs and replaces all of them, the power reduction is 270 W or 0.27 kW.

Table F1: Generation Mix for Pakistan, 2021

Fuel	KE Generation		CPPA-G Generation	
	Generation Quantity (GWh)	Percent (%)	Generation Quantity (GWh)	Percent (%)
Natural Gas	3,420.59	26.08	14,496.43	11.22
Liquefied Natural Gas	4,778	36.43	26,983.81	20.89
RFO	4,265	32.52	6,331.06	4.90
Coal	453	3.45	27,547.78	21.33
Hydro	0	0.00	38,800	30.04
Nuclear	0	0.00	10,871	8.42
Other Renewables (Solar, Wind)	200	1.52	4,122	3.19
Total	13,116.6	100%	129,152.1	100%

Source: Data in this table are from the 2021 NEPRA annual report (NEPRA, 2021).

We assume that liquefied natural gas is same as natural gas throughout the calculations. We multiply the average heat rate for the power plants (natural gas/RFO/coal) power plants in Pakistan, based on NEPRA's reports (NEPRA, 2021), by the carbon intensity of the fuel (natural gas/RFO/coal). These calculations allow us to account not only for the generation fuel type, but also for the efficiency of plants operating in Pakistan.

These calculations of emissions intensities are shown in Table F2.

Table F2: Average Plant Heat Rates and Emissions Intensities of Fuels

Generation Fuel	Power Plants' Average Heat Rate (MMBtu/MWh)	Carbon Intensity of Fuel (kg CO_2/MMBtu)	Emissions Intensity (kg CO_2/MWh)
Natural Gas	8.7	52.9	460
RFO	14.1	75	1,060
Coal	97	12	1,170

We use these emissions intensities by fuel type, in conjunction with the generation mix information in Table F1, to calculate the emissions for KE.

We first do so for the units KE purchased from its own generation basket. This is quite straightforward to calculate as we know the quantities generated by fuel type in the KE system generation. We multiply these by the emissions intensities from above. Results are presented in Table F3.

Calculating the emissions from generation of the electricity purchased from CPPA-G requires a few additional steps. First, we assume that the generation mix of the units

Table F3: Emissions from KE System Electricity Generation

Generation Fuel	Contribution to KE (GWh)	Contribution to KE (MWh)	Emissions Intensity (kg CO_2/MWh)	Emissions Total by Fuel (kg CO_2)
Natural Gas	8,198.59	8,198,590	460	3,771,351,400
RFO	4,265.00	4,265,000	1060	4,520,900,000
Coal	453.00	453,000	1170	530,010,000
Sum				8,822,261,400

purchased from CPPA-G matches the proportions of CPPA-G's overall generation. We calculate those proportions, still assuming that liquefied natural gas is the same as natural gas. Results are in Table F4.

Table F4: CPPA-G Generation

Generation Fuel	CPPA-G Generation (GWh)	Proportion of CPPA-G's Generation
Natural Gas	41,480.24	0.321
RFO	6,331.06	0.049
Coal	27,547.78	0.213
(Hydro)	38,800	0.300
(Nuclear)	10,871	0.084
(Renewables)	4,122	0.032

We know from the NEPRA report (NEPRA, 2021) that KE purchased 6,370 GWh from CPPA-G in the 2020-21 fiscal year. We assume that these units that KE purchased from CPPA-G were generated according to the overall CPPA-G mix shown in Table F4. With this information, we can calculate the CO_2 emissions from the electricity units that KE purchased from CPPA-G. We multiply the proportions in the far right column of Table F4 with 6,370 GWh and get the results shown in Table F5.

We next sum the emissions from the electricity units purchased from KE (8,822,261,400 kg CO_2) in Table F3 and the emissions from the electricity units purchased from CPPA-G (2,748,566,671 kg CO_2) in Table F5. We then convert this total of 11,570,828,071 kg CO_2 to tons, resulting in an estimated 12,754,639 tons of CO_2 per year from the generation of the electricity units purchased by KE.

Table F5: Emissions from the Electricity Generation of KE's Purchases from CPPA-G

Generation Fuel	Contribution to KE (GWh)	Contribution to KE (MWh)	Emissions Intensity (kg CO_2/MWh)	Emissions Total by Fuel (kg CO_2)
Natural Gas	1,964.94	1,964,940.16	460	903,872,472
RFO	299.91	299,905.55	1,060	317,899,879
Coal	1,304.95	1,304,952.41	1,170	1,526,794,320
Sum				2,748,566,671

F3.2 CO_2 Emissions Avoided due to ABC Installation

We first calculate the proportion of generation attributed to each of the fuels potentially responding to the changes in demand. First, we assume that the marginal units purchased are from the KE generation basket, not CPPA-G. Further, we assume that the fossil fuel (natural gas/RFO/coal) generation in the KE generation responds to the changes in demand and that this response is proportional to their generation mix. It is reasonable to assume that nuclear power and renewables do not respond to changes in demand. Hydropower could be the marginal responder, but it is very unlikely; the zero marginal cost of hydropower makes it much cheaper than oil, coal, or gas generation.

Based on these assumptions, we calculate the proportion of responding generation that is contributed by each of these fossil fuels:

$$\textbf{Natural gas: } (17.9 + 31.8)/(17.9 + 31.8 + 10.6 + 28.0) = 49.8/88.3 = 56\% \tag{A1}$$

$$\textbf{RFO: } 10.6/88.3 = 12\% \tag{A2}$$

$$\textbf{Coal: } 28.0/88.3 = 32\% \tag{A3}$$

We then deploy the average emissions intensity for each of the fossil fuel sources, as shown in Table F2.

To calculate a blended estimate of the reduction in CO_2 per kWh reduction of electricity services consumed, we assume that the marginal generators are proportional to the generation from oil, coal, and gas and weight these according to the proportion that each fuel contributes to the generation mix, as follows:

$$= (460 \times 56\%) + (1,060 \times 12\%) + (1,170 \times 32\%) \tag{A4}$$

$$= 760 \text{ kgCO}_2/\text{MWh} \tag{A5}$$

$$= 0.76 \text{ kgCO}_2/\text{kWh}. \tag{A6}$$

This calculation provides our basic estimation of the reduction in CO_2 per kWh reduction of electricity services consumed: 0.76 kg CO_2/kWh.

There are some caveats to this calculation. As mentioned above, we assume that plants generating electricity from fossil fuels respond. If hydro generation responds, the emissions would be lower. This calculation also ignores upstream fuel effects, like methane leakage, which would make the result higher if included. Further, it is possible that the generation response is not proportional across the fossil fuels.

To provide upper- and lower-bound estimates of the reduction in CO_2 per kWh reduction of electricity services consumed, we can alternatively assume that the marginal generation is either strictly natural gas (the least carbon intensive of the three fuels) or RFO (the most carbon intensive of the three fuels). This provides us with the range of estimates in Table F6.

Table F6: Change in CO_2 Emissions per Change in Electricity Generated, by Fuel

Fuel(s)	Change in CO_2 per Generation Change (kg CO_2 /kWh)
Natural Gas	0.46
Blended Generation Fuels	0.76
RFO	1.06
Coal	1.17

Notes: We use these numbers in our calculations in Section F of the paper.

We use these calculations to estimate the change in the CO_2 emissions from electricity generated, depending on which of these fuels is the marginal fuel: natural gas, residual fuel oil, coal, or the responsive blend calculated earlier. We present these calculations in Table F8.

We know from Table F7 that the change in the quantity sent out per feed line as a result of the ABC intervention is -97,213 kWh per month. We multiply that amount by the change in the CO_2 per kWh generated via each fuel, and convert to metric tons of CO_2 per feeder-line per year. To aggregate these avoided CO_2 emissions up, we multiply the per feeder-line numbers by either the 398 high loss feeder-lines in Karachi (our conservative estimate) or the 2000 total feeder-lines in Karachi (an upper bound estimate), providing us with two estimates of the aggregates tons per year in avoided CO_2 emissions in Karachi, as a result of the intervention. Lastly, we compare these reductions to the overall emissions that are from the electricity units purchased by Karachi Electric, as calculated above in Section F3.1.

We see in Table F8 that the reduction in CO_2 emissions resulting from the approximately 400 high-loss feeder-lines being converted to ABCs, would result in a reduction of CO_2 emissions somewhere between 1.67% and 4.26% of the emissions due to electricity generated for KE.

Table F7: Effect of Theft-resistant Cables on Electricity Sent Out

	Quantity Sent Out (kWh per month)	
	Level	IHS
	(1)	(2)
ABC	−97,213.292***	−0.102***
	(18,433.656)	(0.023)
Outcome Mean Level	920,981	920,981
Observations	47,575	47,575
feeder-line FE	✓	✓
IBC-Month FE	✓	✓

Notes: Data are at the feeder-line level. ABC is a binary indicator that equals 1 when the feeder-line has transformers with ABC installed, and equals zero otherwise. All regressions include feeder-line and IBC-by-month fixed effects. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table F8: Change in CO_2 Emissions per Change in Electricity Generated

			Aggregated: High-Loss Feeders	
Generation Fuel(s)	Δ in CO_2 (t CO_2) / Δ Generation (MWh) (1)	Δ in CO_2 Emissions per Feeder (tons) (2)	Δ in CO_2 Emissions per Year (tons) (3)	% of KE's Annual CO_2 Emissions from Generation (4)
Natural Gas	−0.46	−536.6	−213,574	1.67%
Responsive Blend	−0.76	−886.6	−352,861	2.77%
RFO	−1.06	−1,236.6	−492,148	3.86%
Coal	−1.17	−1,364.9	−543,190	4.26%

Notes: The steps leading to these results are detailed in Appendix F3. Column 1 is based on the numbers reported in Table F6. Column 2 is calculated by multiplying the values in column 1 by −97,213 kWh per month, which is the reduction estimated in Table F7 as the reduction in quantity sent out to a feeder-line per month as a result of the ABC installation. Column 3 is calculated by multiplying column 2 by 398, based on the utility's 398 high-loss feeder-lines. Column 4 is calculated by dividing column 3 by 12,754,639 tons of CO_2, which was our estimate for the total CO_2 emissions for generating the units of electricity (kWh) that KE purchased per year.

Table F9: Change in CO_2 Emissions per Change in Electricity Generated, by Generation Fuel

			Aggregated: High-Loss Feeders	
Generation Fuel(s)	Δ in CO_2 (t CO_2) / Δ Generation (MWh) (1)	Δ in CO_2 Emissions per Feeder (tons) (2)	Δ in CO_2 Emissions per Year (tons) (3)	% of KE's Annual CO_2 Emissions from Generation (4)
Natural Gas	−0.46	−536.6	−213,574	1.67%
Responsive Blend	−0.76	−886.6	−352,861	2.77%
RFO	−1.06	−1,236.6	−492,148	3.86%
Coal	−1.17	−1,364.9	−543,190	4.26%

Notes: Column 1 is based on the numbers reported in Table F6. Column 2 is calculated by multiplying the values in column 1 by −97,213 kWh per month, which is the reduction estimated in Table F7 as the reduction in quantity sent out to a feeder-line per month as a result of the ABC installation. Column 3 is calculated by multiplying column 2 by 398, based on the utility's 398 high-loss feeders. Column 4 is calculated by dividing column 3 by 12,754,639 tons of CO_2, which was our estimate for the total CO_2 emissions for generating the KE units of electricity purchased per year (see end of Section F3).

Table F10: Scenarios of Expected Household Reductions in Monthly Electricity Bill, by Season

		Winter	Spring/Fall	Summer
(a)	kW Reduction per Household	0.27	0.27	0.27
(b)	Average Hours of Bulb Use per Day	5.5	4.5	3
(c)	Days in Month	30	30	30
	Expected LED Savings per Month (kWh) = a × b × c	44.55	36.45	24.30

Notes: Average hours per day are based on differences in sunrise and sunsets across seasons.

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