The Economic and Environmental Effects of Making Electricity Infrastructure Excludable*

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Abstract

Electricity theft occurs when individuals cannot be excluded from accessing services. We study the impacts of an infrastructure upgrade in Karachi, Pakistan – converting bare distribution wires to aerial bundled cables (ABCs) – that was intended to prevent illegal connections. ABCs reduced unbilled consumption, increasing both the number of formal utility customers and per customer usage. ABC installation also decreased the utility's annual CO_2 emissions via reduced electricity generation. Resulting changes in consumer surplus vary by consumer type (previously informal versus always formal) and depend on reductions in electricity rationing and the cost of prior illegal grid connections.

Keywords: infrastructure, electricity, climate mitigation
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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). Prior literature argues that this poor service quality stems from an inability of electricity distribution companies to recover the full cost of services delivered due to high subsidies, bill non-payment, and electricity theft. Distribution companies often then resort to electricity rationing to limit the resulting financial burden (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 an infrastructure upgrade that impedes illegal connections to the electricity grid in Karachi, Pakistan and, in doing so, aims 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 consisted of converting bare low voltage distribution wires to aerial bundled cables (ABCs), which are twisted, insulated cables that prevent connections that bypass meters.

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).[1] The technology, however, is less common in South Asia and

[1] Locating distribution lines underground is often optimal, but it is the most expensive option and geographically infeasible for many distribution companies. Utilities instead use aerial lines, which can be bare wires or ABCs. 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).

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.[2] This component 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). Further, higher losses require more electricity generated per unit sold to end consumers and, given electricity generation in these countries is dominated by fossil fuels (IEA/OECD, 2018), higher losses mean greater CO_2 emissions.

Karachi Electric (KE), the distribution company serving the greater Karachi area, introduced ABCs in 2015 with the goal of making the electricity infrastructure excludable. This paper provides causal evidence on the impacts of this supply-side technology on the utility's financial measures, consumer outcomes, and avoided emissions – each of which is not obvious *ex ante*. Even with improved cables installed, consumers may use other channels to keep their consumption unbilled (e.g., manipulating meters), thereby offsetting ABCs' effects. If losses do decrease, overall generation and CO_2 emissions may

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.

[2]Also referred to as non-technical losses.

remain the same or even increase, depending on how overall consumption responds. The effects on consumers are equally ambiguous, as they differ across consumer types (e.g., formal versus informal) and depend on the extent to which electricity rationing changes after conversion from bare wires to ABCs.

Pakistan is a suitable setting for this study due to its high losses and location in South Asia, the region with the most power outages in the world (Zhang, 2018). As of FY 2019-2020, Pakistan's distribution companies reported electric power T&D losses between 9% and 39%, with KE's losses at 19.7% (NEPRA, 2020). With 63% of the country's electricity generated from burning oil, gas, and coal (EIA-OEA, 2018), losses both contribute to CO_2 emissions and impede the country's ability to pay for the imported fossil fuels required for generation, thereby necessitating rationing.

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

Our identification strategy is based on the assumption that, conditional on fixed effects, the roll-out of ABCs 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, feeder-lines' historical loss). Additionally, we control for changes across KE's management offices (called integrated business centers, or IBCs) or across the city over time (e.g., management changes, 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 data-sets, comprising utility data and our own household survey data. Utility data include information on the timing and location of ABC conversion, as well as monthly distribution losses and revenue recovery for more than 2,100 feeder-lines over three years. Panel data on billing-related outcomes for approximately 3,000 residential utility customers enable us to investigate the mechanisms of ABCs' effects. Lastly, survey data that we collected in fall 2021 for these 3,000 customers permit us to better understand ABCs' effects on consumers.

Our analyses provide four key insights on losses and the impacts of a supply-side technology designed to abate them. First, the conversion of bare wires to ABCs significantly and meaningfully reduced unbilled consumption by 8.2 percentage points, a 31% reduction compared to the mean. These effects persist for at least two years after installation, indicating that this was not just a short-run effect of removing illegal connections (which individuals are able to reconnect) during the installation process. Bill payments significantly increased, but to a lesser (and noisier) extent. The greater the intensity of ABC conversion within a feeder-line, the larger the effects were on both measures. Further, the infrastructure improvement had the greatest impacts on unbilled consumption (bill payments) among the feeder-line areas with the highest unbilled consumption (lowest bill payment) prior to the intervention.

Evidence indicates that these financial gains come via two channels. First, the number of formal residential utility customers significantly increased soon after ABC conversion, suggesting that previously informal consumers quickly learned that unbilled consumption was no longer feasible and switched to formal, billed connections. Second, among formal customers, ABC 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 ABC conversion, they shifted all consumption to their formal connection.

What does this mean for consumers? Ex ante, we expect consumers to be worse off given that ABCs result in higher electricity bills, on average. Yet, customers that always used only formal connections are no worse off than before and may even be better off if ABCs induce a reduction in electricity rationing. For households that previously used "kundas" – illegal connections to low-tension cables – the changes in their surplus also depend on the price they paid for their kunda.[3] Overall, we estimate that consumer surplus decreases on average by 1 to 2.60 USD per month per household due to ABCs. Further, analyses of utility load shedding and household survey data indicate that rationing decreased on average following ABC conversion.

Finally, we find that electricity generation, as proxied for by electricity transmitted to feeder-lines within the distribution system, also decreased. We use this estimate, in conjunction with information on the CO_2 emissions associated with KE's marginal generation, and find that the reduction in CO_2 emissions from ABCs is approximately 1.7% to 4.3% of the utility's annual emissions from electricity generation.

This paper makes four main contributions to the literature on the provision of services in developing countries and the environment. First, the study provides evidence on a path to mitigate the financial crises facing utilities in many developing countries.[4] Although existing studies provide evidence on efforts to mitigate high subsidies and inter-

[3]Through focus groups in fall 2021, we learned that often informal groups facilitate kundas and a household must pay an upfront connection fee to the kunda provider plus a monthly kunda fee.

[4]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).

ventions 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 an even more fundamental gap in the literature by estimating losses.

Second, these results show that a purely supply-side reform — in this case, an infrastructure 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, although we find improvements in both utility finances and service delivery following ABC installation, we find no significant differences in customers' trust in the utility. In fact, customers in ABC-converted areas are more likely to believe that the utility makes billing errors. Together, these findings suggest that moving to an equilibrium with greater willingness to pay will also require complementary demand-side reforms targeting bill payment.

Third, this paper provides a framework for conceptualizing changes in consumer surplus. Related studies address inequities in the effects of supply-side interventions along poverty lines (McRae, 2015a; Jack and Smith, 2020). Our study adds new dimensions for conceptualizing heterogeneous effects of utility interventions: formal versus informal consumers and consumers for whom rationing is binding versus non-binding.

Finally, the paper provides insights on how development – and infrastructure specifically – affects the environment.[5] Recent empirical evidence indicates that upgrades in infrastructure quality can increase environmental burdens, albeit not always (Asher, Garg and Novosad, 2020; Meeks et al., 2023). Evidence on the extent to which this infrastructure improvement reduces the wedge between energy supplied and energy produced

[5] Jayachandran (2021) provides a recent discussion as to how the effects of technological and infrastructure improvements are often ambiguous, ex ante. Technological progress may shift the supply curve outward to expand production (and the associated environmental stresses), or it can reduce the quantity of natural resource inputs needed in production processes.

is important if the technology provides a lower-cost and less polluting path to increase available electricity capacity without constructing new generation (Munasinghe, 1984).

The paper proceeds as follows. Section 2 provides background information on electricity distribution in Karachi and recent infrastructure improvements. Section 3 provides a framework for conceptualizing ABCs' impacts. Section 4 details the utility data and our household survey. Section 5 describes the empirical models underpinning our estimations. Section 6 presents results on ABCs' impacts on utility-level outcomes. Section 7 addresses changes in consumer surplus in response to the upgrade. We extend the analyses to illustrate the implications for CO_2 emissions in Section 8, and Section 9 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 established a regulatory entity, National Electric Power Regulatory Authority (NEPRA).[6] Yet the sector continues to struggle with frequent outages and financial challenges, particularly high incidences of unbilled consumption and non-payment of bills.[7] On top of this, tariffs historically were set substantially below the costs to supply electricity (Munasinghe, 1984). Together, these challenges mean that the distribution companies achieve full cost recovery on only a fraction of the units supplied by generation companies and are trapped in a sub-optimal equilibrium with overburdened infrastructure, high losses, intermittent load shedding, and growing

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

[7] According to NEPRA data, average T&D losses were 17% and average bill recovery rate was 90.5% in the fiscal year 2021-22. Note that T&D losses include technical losses due to dissipation of electricity along T&D lines and non-technical losses due to unbilled consumption.

circular debt.[8]

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%.[9] This means that any reduction in generation per unit of electricity sold to consumers would yield lower CO_2 emissions. 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.

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. KE, which is a vertically integrated and privately owned power utility, is the sole provider of electricity services in Karachi.[10] 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 local offices (IBCs), which handle electricity distribution, billing, and collection in their respective areas. 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.

[8]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.

[9]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). 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).

[10]KE is a publicly listed company with the Government of Pakistan holding 24% ownership, while the remaining shares are owned by a consortium of private investors.

Kundas, informal and unauthorized connections to the main electricity distribution cables, are a common sight in many communities in Karachi.[11] The use of kundas on bare wires mean that the electricity infrastructure is nonexcludable and KE is well aware that kundas are the main source of unbilled consumption. Thus, prior to the ABC conversion, its staff continuously monitored these high loss areas, disconnecting kundas and fining perpetrators. 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 are removed early in the morning to avoid detection. This is particularly common in the hot, summer season, when households are using electricity for the purposes of air conditioning.

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.

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 typically either buried underground or are comprised of covered conductors, such as aerial bundled cables (ABCs). Distribution companies

[11] 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 PMT, and low-tension cables (220-440V) carrying electricity from the PMT to the customers. A kunda is usually hooked on the low-tension cables originating from the PMT.

in lower income countries have historically installed the least cost option: bare wires. We summarize distribution network technologies in these sub-sections and provide more detail in Appendix A.

2.3.1 Distribution System Technologies

Bare distribution lines are prone to weather and storm damage (e.g., puncturing by trees) and therefore outages, safety challenges (e.g., electrical shock, fire risk, accidental contact with people and animals), environmental concerns (i.e., extensive tree clearance required), 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 unbilled consumption typically limit distribution companies' revenue and therefore their ability to cover such infrastructure investment costs (International Energy Agency, 2020) .

ABCs are not a new technology. 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.[12] 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-

[12] 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). More detailed information on ABCs is provided in Appendix A.

Engineering studies indicate the ABCs can eliminate unbilled consumption due to kundas. Although these studies indicate that ABCs can also reduce naturally-occurring technical losses, they represent a small fraction of T&D losses in high loss settings. Therefore, any reduction in losses due to ABCs in settings such as ours will be predominantly driven by reductions in unbilled consumption (Abdollahi et al., 2020).

2.3.2 ABCs in Karachi, Pakistan

In an effort to decrease unbilled consumption, KE launched an initiative to convert bare wires to ABCs. ABC conversion began in 2015 as a pilot intervention in a small number of PMTs and was later expanded in some 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 ABCs between 2014 and 2021, in terms of the PMTs on which ABCs were installed. Appendix maps (see Figure B1) depict the installation spatially across one IBC in Karachi over time.

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

3 Conceptual Framework

In this section, we model ABCs' impacts on unbilled consumption. We conceptualize how ABCs could benefit producers (the distribution company), with potential societal effects due to a reduction in generation yielding lower emissions. We discuss how the effects on consumer surplus are ambiguous, yet with a simple model we can predict potential outcomes to better understand our empirical results.

3.1 Producer: The Electricity Distribution Company

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.[13] The customer's consumption (kWh) is measured via an electricity 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, $P_{effective}$. The incidence of unbilled consumption varies across feeder-lines. Given the high incidence of unbilled consumption, we do know that $P_{effective}$ is substantially less than P_f and this contributes to the utility's budgetary constraints.

The budget constraints affect electricity supply and necessitate electricity rationing. To do so, KE categorizes feeder-lines as high or low loss, with high loss areas defined as

[13] We assume a single per unit price for simplicity; however, our results extend to more complex pricing mechanisms.

those where KE recoups a lower rate of payment for electricity delivered (i.e., the feeder-lines with high losses and low bill payment). KE then varies the amount of load shedding across high and low loss areas, with feeder-lines with higher losses having greater rationing (lower quantity supplied to the feeder-line, with more hours of load shedding), while the reverse is true for feeder-lines designated as low loss.

ABCs have the potential to make electricity infrastructure excludable, by limiting the feasibility of kundas and thereby shifting their users to formal connections. If the ABCs do prevent kundas, then we expect KE to be better off, as this would decrease the difference, on average, between P_f and $P_{effective}$. Empirically, if the utility is better off, we expect to see an increase in the number of formal consumers, a reduction in unbilled consumption, and improvement in bill payment.

3.2 Consumers: Both Formal and Informal

The effects of ABCs on consumer surplus are less obvious. While intuitively an increase in the effective price faced by consumers and a reduction in their overall consumption would suggest a reduction in consumer surplus, the effects of ABC installation are more nuanced. In particular, we show that the effects of ABC installation vary across formal and informal consumers, and are affected by the level of rationing.[14]

While a more detailed framework is presented in Appendix C, we note here that the installation of ABCs does not affect the price faced by formal consumers (P_f) and therefore should not reduce their surplus. In fact, a reduction in load shedding may increase the quantity of electricity services consumed, thereby increasing their surplus.

Any reductions in consumer surplus then are driven by informal consumers, who previously consumed electricity at a lower effective price and would have to adjust their consumption after formalization. As noted by Haider (2020) and supported by our focus

[14] It is possible for a consumer to be both formal and informal (i.e., use a formal connection for some use, but also use a kunda or meter tampering). While we may appear to abstract away from this for simplicity, note that mathematically ”splitting” the consumer into two is equivalent.

group discussions, even informal users pay some price for their electricity, often a fixed monthly fee for the kunda services. Thus, by being forced to shift to formal usage, the surplus of previously informal consumers should fall.[15] Yet, the decrease may not be as large as intuition would suggest, as the shift to paying P_f is not from an effective price of zero, but rather from some fixed payment. Finally, it may indeed be the case that a reduction in load shedding may *increase* the surplus of some informal users as well, if it leads to a reduction in rationing and said rationing was previously a binding constraint.

4 Data

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

4.1 Utility Feeder-line and ABC Conversion Data

We assembled a comprehensive and unique dataset including estimates of feeder-level unbilled consumption, percentage of bill payment, utility claims, consumer complaints, consumer numbers and date of ABC conversions of PMTs from KE. [16] Our final monthly dataset covers 2,163 feeder-lines in Karachi.

Unbilled consumption and bill payment. KE estimates unbilled consumption and bill payment via two variables: *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. Note that this is in essence an estimate of total T&D

[15] As while there may be a price for the kunda, it must still be lower than the cost of a formal connection.

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

losses, as there is no way to distinguish between unbilled consumption and technical losses. However, given the engineering literature indicates that the major component of these losses are unbilled consumption (Abdollahi et al., 2020), changes in this variable are an acceptable proxy for a changes in unbilled consumption.[17]

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

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.

ABC Installation. KE provided the dates when ABCs were installed in each PMT. We observe the installation record through January 2021. To match these data with feeder-level monthly variables, we create two measures for ABC adoption. First, we define a binary indicator for whether a feeder-line has at least one PMT with ABCs installed. Second, we calculate the ratio of the number of PMTs with ABCs installed relative to the number of total PMTs in a feeder-line.

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 electricity

[17] See Appendix 2.3 for details.

units and amount, the amount and date of payment, total due to KE, and the billing category mode (BCM).[18] 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 PMTs. 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 IBC offices. Within these feeder-lines, we restrict to PMTs 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 PMTs from which to select. We randomly select 150 PMTs, ensuring that PMTs both with and without ABCs are represented in the list. Selected PMTs serve, on average, 202 residential customers each. Within PMTs, we limit our sample to residential customers with active accounts and then randomly select 20 customers per PMT to survey.

The questionnaire collects information on basic house characteristics, household 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.

[18] 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.

From these survey data, we learn about the households in this setting and their general demographic information (Appendix Table D1). 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 constructed of pucca (i.e., bricks and cement) materials 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 D2), 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 Unbilled Consumption and Bill Payment

To estimate the economic effect of the infrastructure improvement, our research design leverages differences over time and across Karachi in the ABC conversion process. The adoption of ABCs follows a staggered process, the timing of which mainly depends on KE's business strategy. Since the roll-out of ABCs creates variations across feeder-lines and over time, we employ a staggered DID approach to identify the causal effect of ABC conversion on feeder-level unbilled consumption 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 unbilled consumption and bill payment (measured via KE variables *losses* and *revenue recovery*, both measured 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 PMT with ABCs 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 ABC 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, or revision of targets. The standard errors are clustered at the feeder-line level.[19]

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

5.2 Validity of Identification Strategy

Our identification strategy takes advantage of variations in outcome measures specific to feeder-lines with ABC conversion relative to feeder-lines without ABC conversion, and in periods before and after the conversion. Based on KE's business strategy, the roll-out of ABC 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 esti-

[19] The results are robust to using alternative clustering approaches as shown in Table D3.

mates. 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 briefly 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 ABC 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 ABC 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 ABC conversion events. Specifically, τ_i denotes the first month when feeder-line i started deploying ABCs at its PMTs, 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 the 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 ABC conversion dummy are small in magnitude and statistically indistinguishable from zero, then there is no evidence of meaningfully differential trends in unbilled consumption and bill payment in advance of the ABC 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 the identification. The remaining concern mainly stems from time-varying feeder-level changes. We address this issue in two ways. 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 ABC installation might be affected by the utility company's anticipation of feeder-level changes, we conduct robustness checks focusing on feeder-lines that are followers of initial ABC conversions according to KE's "ring-fencing" strategy and therefore their conversion schedules are likely to be exogenous.

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 ABC conversion of one feeder-line does not affect other feeder-lines that have not yet been converted. Since the ABC conversion work was conducted by an outside vendor, we are able to exclude the possibility that the utility's labor force was diverted from the non-ABC areas. Moreover, the load shedding in Karachi is assigned at the feeder-line level and determined by each feeder-line's loss category. Therefore, the load-shedding in non-ABC areas is unlikely to be affected. One may be concerned that households located in ABC-converted areas instead connect their kundas to nearby non-ABC feeder-lines. This concern is alleviated due to KE's "ring fencing" strategy – once the ABC installation starts at a PMT, the company will convert other PMTs 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 ABCs using panel data on residential customers' billing-related outcomes.

We conduct both event studies and DID regression analyses of ABCs' impacts on residential customers. For residential consumer i served by PMT 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 PMT j already has ABCs installed in month t. We add consumer fixed effects (α_i), month fixed effects δ_t, and PMT by month-of-year fixed effects $\gamma_{j\tau(t)}$ to capture unobservable factors. Standard errors are clustered at the PMT level.

6 Effects of Infrastructure Upgrades on Electricity Utility

In this section, we present results from our baseline model that suggest that infrastructure improvements, in the form of ABC installation, resulted in a reduction in unbilled consumption and increased bill payments. To understand the channels through which these impacts occurred, we also investigate whether ABC installation affected the number of utility customers or customer bill payment behaviors.

6.1 Unbilled Consumption and Bill Payment

6.1.1 Main Results

We investigate the effects of ABC 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 ABCs on at least one PMT and those that were not (the "untreated"), controlling for both IBC-by-month and feeder fixed effects.

These event studies provide two key results. Figure 2 shows that the estimated coefficients for the leads of the ABC conversion dummy are small in magnitude and statistically indistinguishable from zero. Hence, there is no evidence of meaningfully differential trends in unbilled consumption and bill payment in advance of the ABC conversion, which provides support for the parallel trends assumption. Second, these results illustrate a significant negative effect on unbilled consumption and a positive effect on bill payment from ABC installation. These effects persist for the duration of the study period.

We further investigate this relationship through DID analysis, as depicted in Equation 1. Results showing the estimated impact of ABCs – using the binary variable indicative of ABC installation on at least one PMT on a feeder-line – on unbilled consumption are in Table 1, Panel A. Results from regressions using our other measure of treatment – the intensity of ABC 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.

The results in both panels tell a consistent story. ABC installation, whether measured as a binary indicator or as a treatment intensity, led to significant reductions in unbilled consumption and increases in bill recovery. In Panel A, the estimates in columns 1 and 3 suggest that unbilled consumption were lower by 6.2 to 8.2 percentage points in feeders with ABCs. This is a reduction of 26% to 32% of the average level in non-ABC feeders. 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 of 6% of the average in non-ABC feeders. Panel B provides evidence that fully replacing all bare wires within a feeder-line with ABCs leads to even larger improvements in unbilled consumption and bill payment. However, supplemental evidence indicates non-linearities in the effect of ABC installation intensity. Specifically, we find diminishing returns on ABCs for bill recovery (Appendix Table D4).

Additionally, we investigate whether the ABCs have heterogeneous effects, depending on the severity of the unbilled consumption and bill recovery problems prior to the upgrade. We classify the initial unbilled consumption or bill payment rates (the monthly average losses or revenue recovery rate variables over January 2018 and June 2018) of the feeder-line into three categories by percentile: low, medium, and high. The ABC indicator is then interacted with binary indicators for feeder-line categories. Results from these analyses are presented in Table 2. We find that the effects of ABC installation increase with the level of pre-intervention unbilled consumption. In other words, unbilled consumption decreased more in the feeders that had higher levels of theft at baseline. Similarly, bill payment increased more among the feeders with medium and low levels of baseline payments.

6.1.2 Robustness Checks

The results presented in Table 1 are robust to a number of checks, which are summarized here (and presented in the Appendix Table D5).

Contemporary Loss Mitigation Policies. Our estimated impact of ABC conversion might be confounded by feeder-line level contemporary mitigation efforts. 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, KE 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 capture feeder-level policies within each IBC. The results, shown in Panel A of Appendix Table D5, are similar to those from our baseline estimates.

"Ring-Fencing" and the Roll-out of ABC Conversion. We leverage the utility company's "ring-fencing" strategy to address the concern that ABC 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 ABC conversion starts, the company tries to cover neighboring regions – to prevent negative spillovers. One might worry about the endogeneity of ABC 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 ABC conversion (i.e., feeder-lines that did not have one of these “first converted” PMTs). 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 ABC conversion date among them. Then, we drop the feeder-line areas if they are among the earliest to have ABCs installed. This process is repeated across all feeder-line areas and we end up having only the followers of ABC conversion in our sample. With this restricted sample, we re-estimate our baseline model and the results are presented in Panel B of Appendix Table D5. 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 ABC conversion process. Our conclusions still hold.

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 ABCs installed, those changes must not affect the 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. 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 alleviate concerns regarding this potential SUTVA violation.

Second, the process of installing ABCs 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 ABCs, the utility outsourced the vast majority of this work to another company. With this work conducted by an outside vendor, the utility's labor resources were not diverted from the non-ABC 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 ABC installation must not connect a kunda to a nearby feeder-line without an ABC 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 ABC 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 PMTs, 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 D5 Panel C). Additionally, we control for the ABC status of neighboring feeder-lines, by adding an indicator for whether there are ABC conversions at PMTs from other feeder-lines located within 100 m, 300 m, or 500 m distances (Appendix Table D5 Panel D). 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 E of Appendix Table D5), we report the aggregated estimates of the average treatment effect on the treated for all timing groups across all periods. The coefficient estimates have the same sign and similar magnitudes as the ones from our baseline model. For robustness, we also estimate event-study models following the approach suggested by Callaway and Sant'Anna (2021) and Sun and Abraham (2021). Appendix Figure D1 presents results from these alternative estimators, which exhibit similar patterns.

6.2 Mechanisms for Utility Effects

A reduction in unbilled consumption could come via multiple channels. We find evidence that the reduction came with an increase in the total number of customers. These results are indicative of ABCs making kundas more difficult, i.e. making electricity excludable. Further, in the absence of informal substitutes, formal customers would want to avoid bill non-payment to prevent disconnection of their formal electricity connections.

6.2.1 Effects of ABC 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 of ABC installation. We investigate this channel through both event studies and regression analyses.

We perform an event study in which the outcome variable is the inverse hyperbolic sine of the number of all types of consumers on a feeder-line over time. Appendix Figure D2 provides no evidence of a statistically significant difference in pre-trends between the ABC "treated" and "untreated" feeder-lines. There is a statistically significant increase in the number of customers following the ABC installation. The increase occurs approximately two months after the installation of the ABCs, suggesting that customers previously using illegal connections learn in the months after ABC installation that kundas are more difficult to connect making them switch to formal connections.

As before, we implement two regression analyses to estimate the impact of ABCs on the number of consumers, one using the binary indicator of ABC installation as the treatment variable, the other using the proportion of PMTs in a feeder covered by ABCs as the measure of treatment intensity. In Table 3 column 1, the outcome variable is the inverse hyperbolic sine of number of consumers – of all types – in each feeder-line. We see a significant effect of ABCs on 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 ABCs on different categories of consumers (agricultural, bulk, commercial, industrial, and residential). We find that overall ABC installation led to a 6.5% increase in total number of customers at the feeder-line level (column 1) and that these changes were driven primarily by an increase in residential consumers (column 6).

6.2.2 Consumers Bills for Electricity Services

Event studies in Appendix Figure D3 indicate that, following the installation of ABCs, both residential consumers' quantity of billed units and the monetary billed amount increased significantly. 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.[20]

The DID regression analyses in Table 4 provide further insights. Panel A shows the average treatment effects of ABCs, similar to those in the event studies. With our binary

[20] In Appendix Figure D4 and D5, 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.

treatment variable indicating ABC installation, we interpret these coefficients as the impact of a PMT being upgraded from the bare wires to ABCs. In columns 1 and 2, the outcome variables are the inverse hyperbolic sine of billed units (kWh) and billed monetary amounts (rupees). Results indicate that the ABC 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 a meter-related issue within a month and whether there were thefts during a month reduced by 11.1 and 3.8 percentage points, respectively.

Panel B shows heterogeneity by expenditure group. Interestingly, the effects of the ABCs 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 the infrastructure improvement in context, we compare them with the costs of ABC conversion.[21] We create four cost scenarios based on data provided by KE. Together, these provide us with bounds on the overall cost of ABCs. As a lower bound, we include the costs of ABC materials alone, not an outlandish assumption given that regular wire replacement labor is required even in the absence of the ABC conversion. As upper bounds for our cost calculation, we use KE estimates of the ABC cost per PMT converted in high-loss areas, both with and without labor included. To convert costs into units comparable to benefits, we divide the cost per PMT by the average number of consumers per PMT. The estimated costs to the utility are between 16,389 PKR per

[21] Additional details on these calculations are provided in Appendix E.

customer and 33,630 PKR per customer (Appendix Table E1). For simplicity, we assume these costs are all upfront, occurring in year 0.

To approximate the benefits to the utility, we use the change in customer payment following the conversion to ABCs, based on the estimated increase in the monetary billed amount from Table 4. Dividing these total benefits per year by the number of consumers in high-loss areas, we get a per-consumer benefit to the utility of 5,729 PKR per year. We assume that ABCs have a ten-year life span and that annual benefits are constant over these ten years.[22] We calculate the net present value of benefits using discount rates of 8%, 10%, and 12%, resulting in per-customer benefits between 42,796 PKR and 56,253 PKR (Appendix Table E2). So, even for our most conservative estimates, the benefits far outweigh the costs to the utility (Appendix Table E3).

7 Changes in Consumer Surplus

In the preceding sections, we analyzed the effect of ABC installation on the utility's bottom line, showing that it reduced unbilled consumption and increased revenue, suggesting that the intervention raised producer surplus. In this section we look at the effect ABCs had on consumers, analyzed from two angles. First, we estimate changes in consumer surplus and government subsidies. Second, we extend the discussion and report evidence of electricity service quality improvements.

Given our previous results, in particular the decrease in units sent out and increase in billed units, we expect consumer surplus to fall following the installation of ABCs. For any decreasing demand curve, we anticipate that a switch from kundas to formal connections would increase the effective price of electricity and reduce consumption, therefore lowering consumer surplus. However, as discussed in the conceptual framework, the actual effects are less clear in the presence of rationing. In particular, formal consumers are

[22]Globally, ABCs' expected life span is between 15 and 20 years. However, KE reports an expected ten-year life span due to the local conditions in Karachi.

in fact weakly better off with ABCs, as there is no change in the price structure and they may even benefit from a reduction in load shedding. For informal customers, the effect is ambiguous, and is a function of three things: the effect and magnitude of changes in rationing, and the kunda fee.

Second, given ABC installation does not change the pricing structure for preexisting formal customers, any fall in consumer surplus is driven by consumers who were previously using kundas to bypass the formal billing system. While it is true that ABCs may decrease consumer surplus in the aggregate, the decrease is driven by a switch from informal to formal consumption. Therefore, it is reasonable to assume that ABCs lower the cross-subsidization of electricity consumption from formal to informal consumers, and may yield higher quality of service for the utility's customers due to lower incidence of load shedding. These latter quality effects are not captured by our surplus calculations.

Regarding total welfare, we note that the amount of subsidy paid by the government falls with fewer units sent out. Under a perfectly competitive market, this would result in an increase in welfare, but a utility is the quintessential natural monopoly, and in the presence of market power, welfare may increase or decrease, depending on whether the subsidy causes the utility to over- or under-produce relative to the optima. Lastly, we wish to emphasize that the welfare results reported in this paper do not account for externalities, such as carbon emissions from electricity generation. Further, any decrease in technical losses due to improved infrastructure is a pure welfare gain.

7.1 Consumer Surplus Calculation

We now quantify 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.[23]

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).[24]

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:

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

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.

The changes in consumer surplus calculated above contain within them the lump-

[23]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.

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

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 5 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.

7.2 Supporting Evidence

We supplement these consumer surplus calculations with evidence on service quality changes. After ABC conversion, there is a decline in hours of load shedding and the number of consumer complaints. Customers in areas with ABCs report experiencing significantly less load shedding than those in areas without ABCs and, consistent with that, these households have more appliances and a greater number of reported hours of appliance use per day.

7.2.1 Load Shedding

Historically, the electricity utility has targeted load shedding according to the loss category of a feeder-line. Given that the utility's financial indicators improved – unbilled consumption fell and bill recovery increased – with ABCs (as shown in Table 1), we expect to see less load shedding in these ABC areas relative to other high-loss areas without ABCs. Leveraging the utility's record on planned outages, we estimate the impact of ABCs on average hours of load shedding per day in a month. Table 6 presents the estimation results. The first two columns use the whole sample while the last two columns focus on high-loss IBC regions. We find unambiguous evidence of reduced load shedding after the ABC conversion, indicating that households are supposed to receive more hours of electricity per day. The coefficient estimate in Column (1) suggests that, on average, ABC conversion decreases daily load shedding by 0.4 hours. The impact is larger among high-loss regions and is increasing in ABC conversion.

7.2.2 Consumer Complaints

With ABCs making illegal connections more difficult to achieve, consumers might make more frequent complaints to the utility (e.g., complaints regarding deterioration of service quality or disputes of bills), which we investigate here. We use the utility's data on consumer complaints at the feeder-line level, and the type of complaints filed, to estimate impacts of ABCs on these outcome measures. Regression results are presented in Table 7, 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. Estimated impacts across the two panels suggest that the rise in complaints was proportional to the increase in consumers. Panel A indicates an increase in total complaints, which is the result of an increase in bill complaints and service requests in combination with a decrease in arrears disputes. In contrast, after the total complaints are divided by the number of consumers within the feeder, the estimates in Panel B are of smaller magnitude. These results suggest that consumer complaints overall decrease (per customer) with ABC installation, which is a function of the significant reduction in technical complaints and is consistent with improvements in service quality.

7.2.3 Suggestive Evidence from Survey Data

Through the household survey data, we can better understand the mechanisms through which ABCs' impacts occurred. Given that our residential consumer survey is cross-sectional, we interpret these results as correlational and supplemental to our main results. Table 8 presents differences in reported service quality for households covered by ABCs, relative to those not yet covered by ABCs.

Consistent with our previous findings on decline in planned outages, households reported fewer hours per day of load shedding in both the summer (column 1) and winter (column 2) among the ABC areas, relative to the non-ABC areas. The estimated reduction in load shedding is approximately one fewer hour of load shedding in areas with ABCs, depending on the season and the expenditure group. Notably, the mean load shedding in the control group is 8.5 hours per day in the summer and 6.9 hours in the winter.

With fewer hours of load shedding, household appliance ownership and use may differ across ABC and non-ABC areas as households can use the appliances more when there are more hours of electricity available. We see greater numbers of both appliances (column 3) and hours of daily appliance usage (column 4).

Lastly, we use data from survey questions designed to elicit respondents' beliefs and perceptions to understand if there are differences across ABC and non-ABC households with respect to the electricity utility, load shedding, and billing/bill payment. Results are presented in Figure 3. Households in ABC areas 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; however, they are also less likely to believe that electricity quality issues (both electricity shortages and load shedding) are problems.

8 Implications for Climate Change Mitigation

Ex ante, the implications of the ABC 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: ABCs 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.

8.1 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 ABCs 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 ABCs' 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 ABC 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.[25] To estimate the impact of ABCs 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 9 show that ABCs 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

[25]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.

sent out, the intervention led to a 10.2% decrease in generation per feeder-line per month (column 2). These results indicate that ABCs 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 are in Appendix F. 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 10. 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 9). 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.

8.2 Comparing ABCs with Other Interventions

To provide a sense of magnitude for these calculations, we compare the ABCs' reductions in billed electricity consumption with the feasible reductions from other technologies. To do so, we convert the ABCs' feeder-line-level reductions into residential consumer-level reductions. From our regressions, we know that ABCs 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 an ABC-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.[26] We then use that estimated reduction to calculate the expected reduction in billed electricity (kWh) per month (Appendix Table F8). 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 ABC-induced reduction we calculated per consumer. Therefore, the reduction from ABCs is equivalent to that of shifting to more efficient lighting.

[26] 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.

9 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 *newly-constructed* distribution lines in settings that are being electrified for the first time in efforts to meet the Sustainable Development Goals.[27] 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 upgraded cables such as ABCs.

In this paper, we present impacts of an infrastructure upgrade in Karachi, Pakistan that prevented illegal connections to the grid, thereby making the electricity infrastructure excludable. We find that ABC conversion both significantly reduced unbilled consumption/theft and increased bill payment. We find evidence that ABCs 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 ABCs making illegal connections to the distribution wires more difficult and, as a result, more customers becoming formal customers of the utility.

From an environmental perspective, despite an increase in both the total number of customers and billed units per customer, the amount of electricity sent out over the distribution system decreased after ABC installation. We estimate that the reduction in CO_2 emissions from ABC installations, *in only* its high-loss feeder-lines is between 1.7% and 4.3% of the utility's annual emissions from electricity generation. In a country that depends on thermal power plants to produce close to 70% of its total electricity, the carbon-

[27] 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).

reducing impact of ABCs is non-trivial.

Finally, our consumer-related results – both the consumer surplus analysis and the results from the household survey – suggest that some consumers are worse off than they were prior to the ABC conversion. The overall fall in consumption (as measured by the amount sent out to the feeder-line) at ABC-treated feeder-lines, even though load shedding decreased, indicates that at least some of the kunda users affected by ABC installation were poorer households for which electricity rationing was not binding. This suggests that while ABCs were effective at reducing unbilled consumption, they ought to be paired with additional pricing and social assistance reforms for the poorest households.

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Figures and Tables

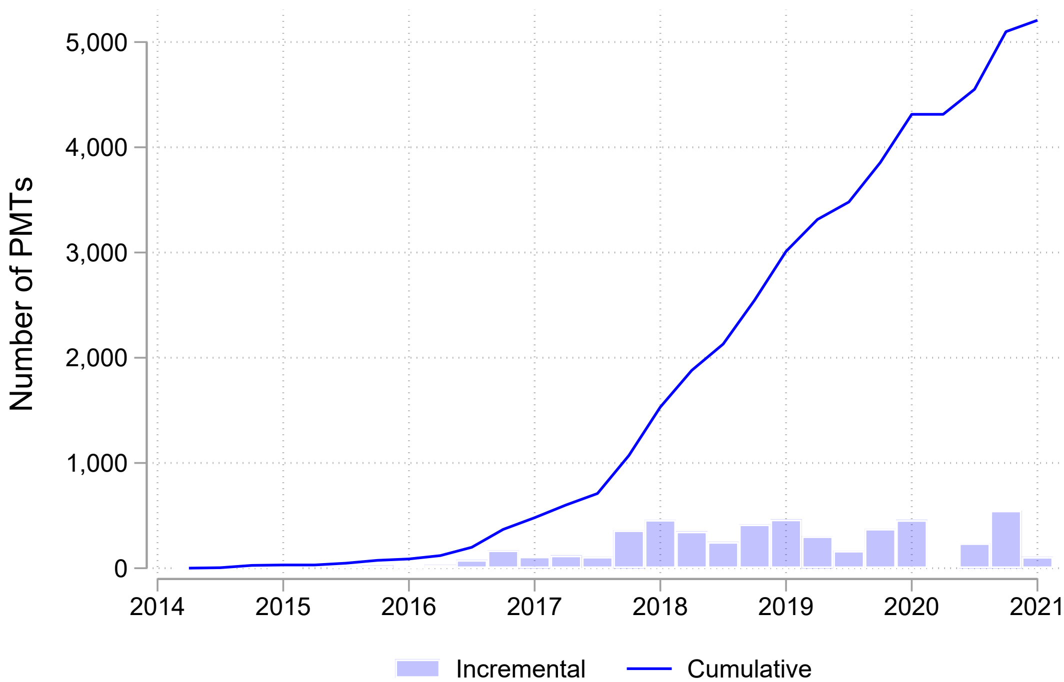

Figure 1: Trend of ABC Installation

Notes: This figure shows the incremental and cumulative number of pole-mounted transformers (PMTs) with ABC installed over time in Karachi, Pakistan.

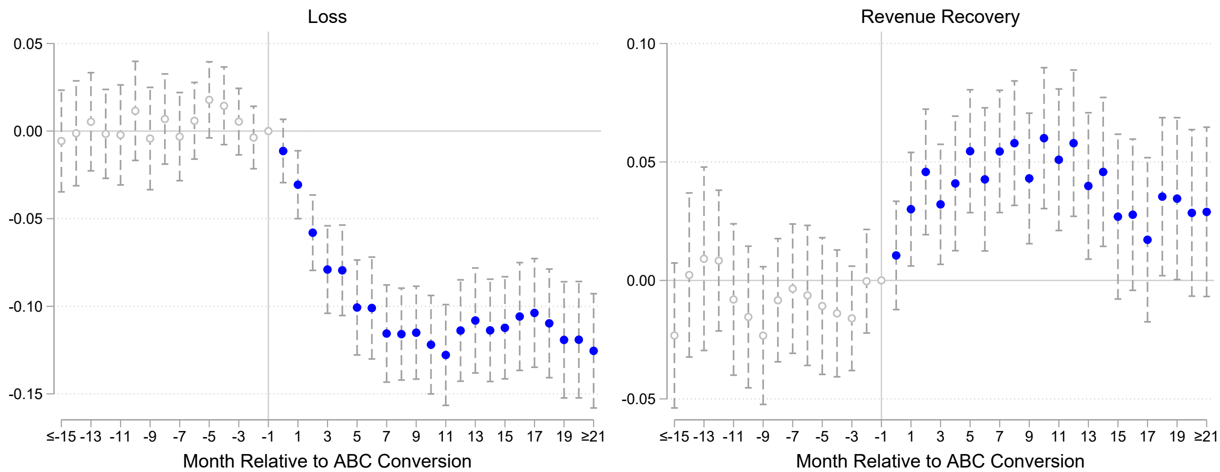

Figure 2: Event-Study Estimates of the Impact of ABCs on Losses and Revenue Recovery

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.

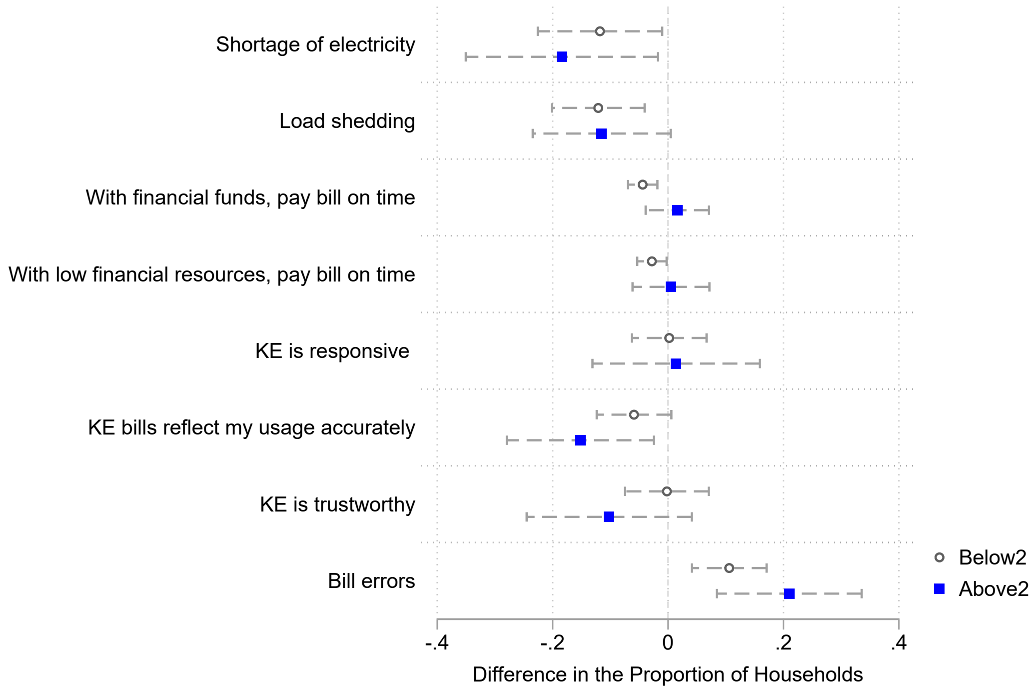

Figure 3: Differences in Household Beliefs Across ABC and Non-ABC Areas

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 PMT 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 PMT level.

Table 1: Impact of ABC Installation 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-line FE	✓	✓	✓	✓
IBC-Month FE	✓	✓		
IBC-Quarter FE			✓	✓

Notes: Data are at the feeder-line level. There are 2,163 feeder-lines in Karachi during the study period. ABC is a binary indicator that equals 1 when the feeder-line has PMTs with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of PMTs with ABCs installed divided by the number of total PMTs 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: Heterogeneous Impacts 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 × Medium Loss	−0.061***		−0.057***	
	(0.016)		(0.016)	
ABC × High Loss	−0.135***		−0.126***	
	(0.030)		(0.029)	
ABC × Medium Revenue Recovery		0.098***		0.073***
		(0.013)		(0.014)
ABC × 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. There are 2,163 feeder-lines in Karachi during the study period. ABC is a binary indicator that equals 1 when the feeder-line has PMTs 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 3: Impact of ABCs on Consumer Number

Variables (IHS)	Total (1)	Agriculture (2)	Bulk (3)	Commerce (4)	Industry (5)	Resident (6)
Panel A: DID Estimates						
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)
Panel B: Intensity of Treatment						
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	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 inverse hyperbolic sine (IHS) of 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 PMTs with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of PMTs with ABCs installed divided by the total number of PMTs 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: Effect of ABCs on Customer Behaviors

	IHS Billed Units (1)	IHS Billed Amount (2)	Not Pay (3)	Payment Ratio (4)	Irregular Bills (5)	Thefts (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	0.087	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	✓	✓	✓	✓	✓	✓
PMT-Month-of-Year 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 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. ABC is a binary dummy that equals 1 if the household is served by a PMT 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 PMT-by-month-of-year fixed effects. Standard errors are clustered at the PMT level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: Effect of ABCs 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 7.1.

Table 6: Impact of ABCs on Load Shedding

	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 PMTs with ABCs installed, and equals zero otherwise. ABC ratio is defined as the number of PMTs with ABCs installed divided by the number of total PMTs in a feeder-line. All regressions include feeder and IBC-by-month. Standard errors in parentheses are clustered at the feeder-line level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Impact of ABCs on Consumer Complaints

Variables (IHS)	All	Bill Complaints	Service Requests	Technical Complaints
	(1)	(2)	(3)	(4)
Panel A: Total Measures				
ABC	−0.079***	0.223***	−0.126***	−0.238***
	(0.023)	(0.031)	(0.041)	(0.032)
Outcome Mean	85.58	5.48	1.73	12.32
Panel B: Per Consumer Measures				
ABC	−0.016***	0.001***	0.002*	−0.018***
	(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-line FE	✓	✓	✓	✓
IBC-Month FE	✓	✓	✓	✓

Notes: Data are at the feeder-line level. The outcome variable is the inverse hyperbolic sine of the number of consumer complaints, including all types of complaints, bill complaints, and service requests. 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: 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 (1)	Winter (2)	(3)	(4)
ABC	-1.173^{***}	-1.015^{***}	0.506^{***}	3.487^{***}
	(0.260)	(0.322)	(0.156)	(0.847)
Control Mean	8.541	6.872	6.833	18.409
Observations	3,068	3,068	3,068	3,068
R-squared	0.125	0.302	0.372	0.198
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 PMT 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 PMT level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 9: Effect of ABCs on Electricity Sent Out

	Quantity Sent Out (kWh per month)	
	Level (1)	IHS (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 PMTs 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 10: 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 F. 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 9 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.

ONLINE APPENDIX

The Economic and Environmental Effects of Making Electricity Infrastructure Excludable

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Zhenxuan Wang Javed Younas

A Background on Electricity Distribution Networks

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.[28] Taken together, substantial investments in distribution infrastructure are expected in the near future.

To better understand the different technology options available for use within distribution networks and and the path towards the ABCs' 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 findings in the following sub-sections.

Overall, distribution network investments are costly, both in terms of time costs and monetary value. 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.

A1 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. 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) and 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

[28] 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).

(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 Technical Background and Historical Use of ABCs

Many high and middle income countries have engineering standards for distribution networks that require components that are more expensive than the most basic components available on the market. In some high income countries, electricity distribution networks are now underground. Being underground makes the distribution system less susceptible to service interruptions and safety concerns than the aerial alternatives, but requires high upfront investment costs (International Energy Agency, 2022). In low- and lower-middle income countries, such high upfront costs mean that underground distribution networks are much less common (La Salvia, 2006).

Aerial distribution networks are the alternative to underground systems. The lowest cost aerial network option is comprised of open cables or bare lines, which have been convention in many settings (Agarwal, Mukherjee and Barna, 2013). These bare cables, however, are prone to weather/storm damage (e.g., puncturing by trees), and therefore, are prone to outages, safety challenges (e.g., electrical shock, fire risk, accidental contact with people and animals), environmental concerns (i.e., extensive tree clearance required), and electricity theft via illegal tapping (La Salvia, 2006; Southern California Edison, 2018).

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" (Pacific Gas and Electric Company, 2021). This covering differentiates the conductor from a bare wire conductor.[29] Aerial Bundled Cables (ABCs), one type of commonly used covered conductor, are twisted and tightly bundled insulated low voltage cables (Pacific Gas and Electric Company, 2021).[30] 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), particularly in areas with dense vegetation and forests (Southern California Edison, 2018).

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

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

[30] 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.

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, but until this time were relatively rarely installed (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.

A3 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 more 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 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) conducted a 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.

A4 ABC Installation in Pakistan

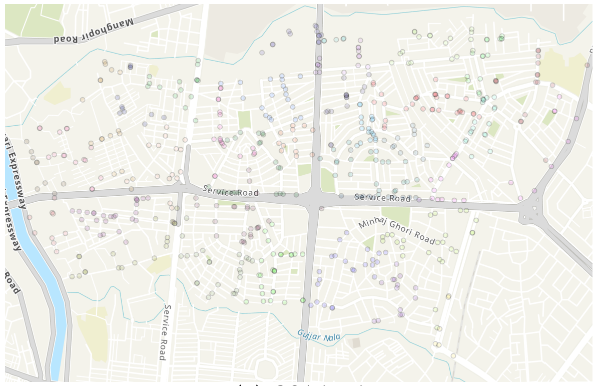
In its 2022 State of the Industry Report, Pakistan's regulator recommended that the country's electricity distribution companies install ABCs in order to reduce losses (NEPRA, 2022). However, theft and ABCs were already major points of discussion for Pakistan's electricity sector. Unbiiled consumption and ways to mitigate them 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

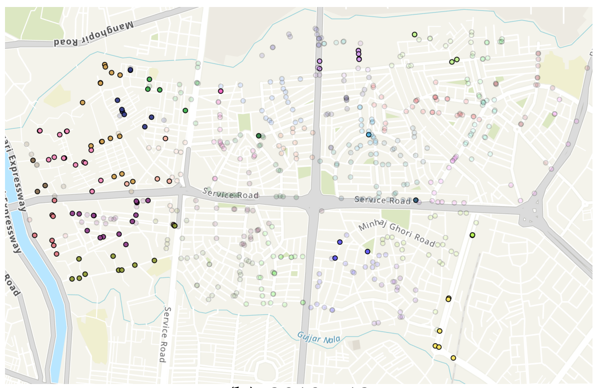
of ABCs is a regular part of Karachi Electric's work to upgrade the network and reduce illegal kundas in Karachi. https://dailytimes.com.pk/703407/k-electric-requests-consumers-understanding-as-it-conducts-annual-preventive-maintenance/

- 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

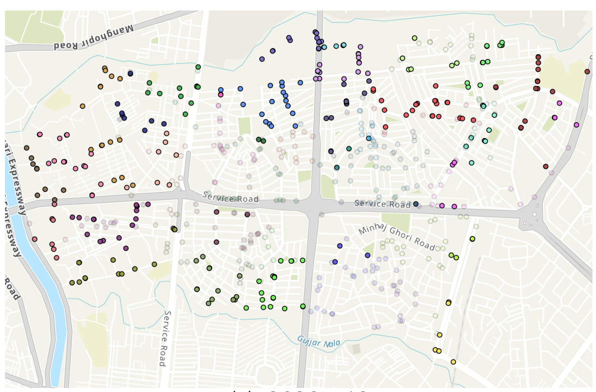
B Maps



(a) 2016m6



(b) 2018m12



(c) 2020m12

Figure B1: ABC Installation at PMTs

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

C A Model of ABCs' 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.

C1 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.[31] 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 recoup a higher rate of payment (i.e., the feeder-lines with lower losses). To operational-

[31] 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.

ize 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.

C2 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.

C3 Formal Consumers: Change in Consumer Surplus

We illustrate the potential impacts of ABCs on the surplus of formal consumers in Figure B2. 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 B2. 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.

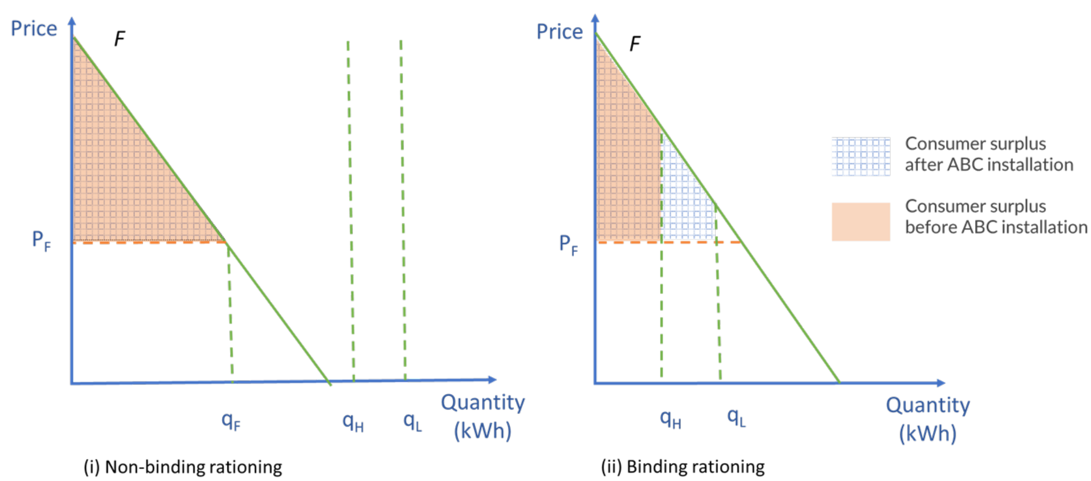


Figure B2: Consumer Surplus of Formal Consumers

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.

C4 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 B3. 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.

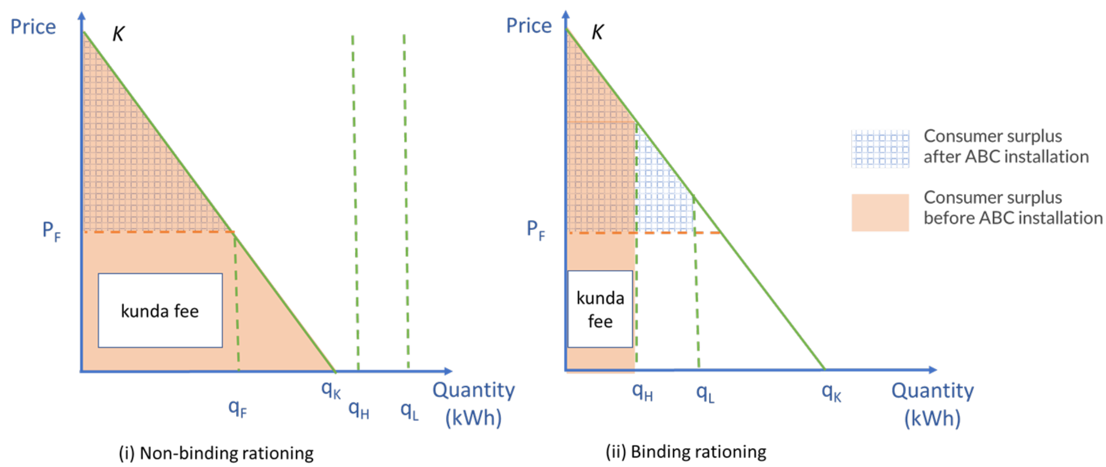


Figure B3: Consumer Surplus of Kunda Users

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.

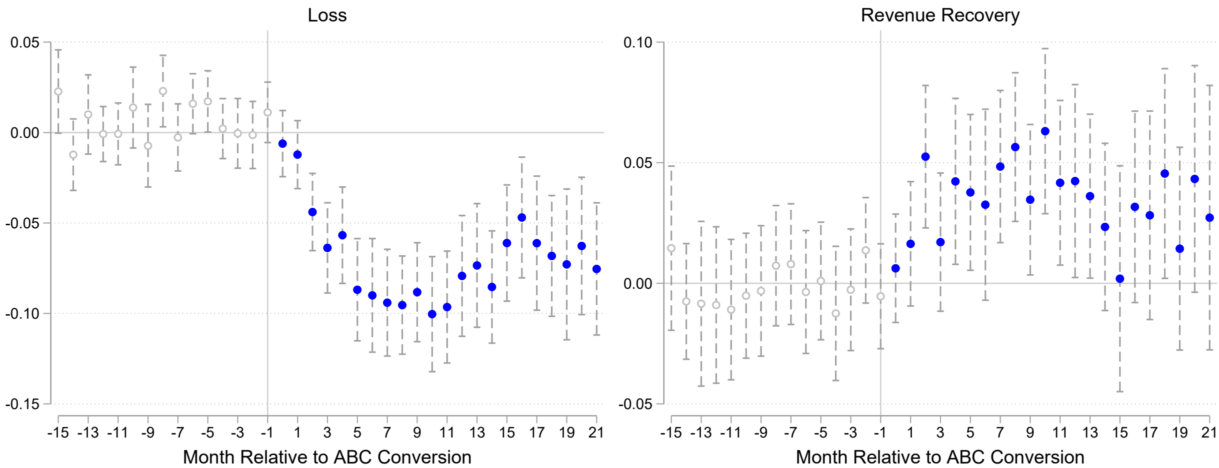
In both scenarios, the consumer surplus is the lightly shaded area below the individual demand curve minus the amount of the monthly kunda fee, as depicted by the unshaded block. In both scenarios – binding and non-binding – before ABC installation, the consumer surplus will depend on the magnitude of 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.

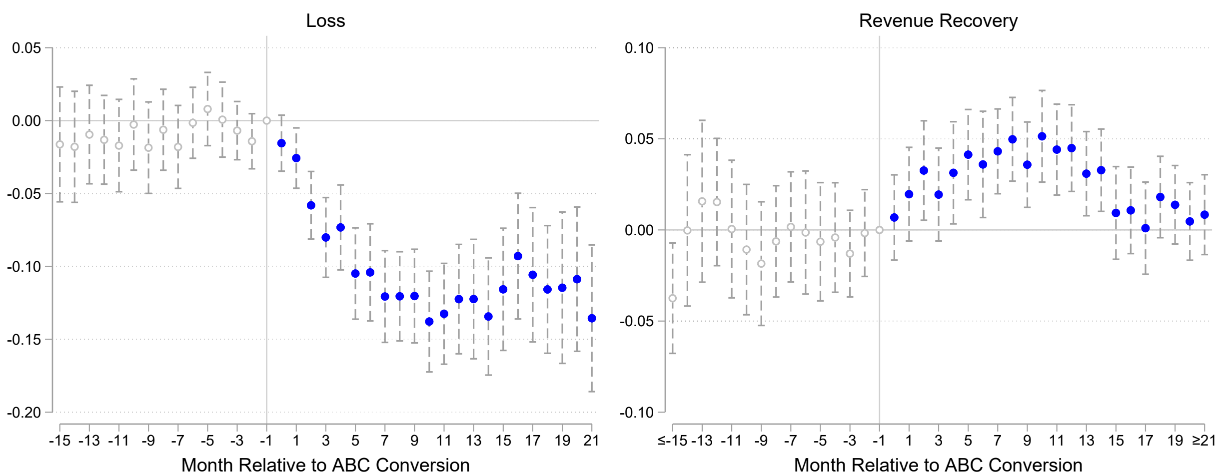
When rationing is non-binding (as on the left), the change from a fixed fee to the state tariff, P_F, will result in a decrease in consumption from q_K to q_F. The consumer surplus is now just the area above P_F, as shaded by the thin crossed pattern. With rationing non-binding, both q_K and q_F are 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.

D Additional Figures and Tables



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



(b) Adjusted Following Sun and Abraham (2021)

Figure D1: Dynamic Impacts on Losses and Revenue Recovery – Alternative Estimators

Notes: We use alternative estimators to address the concerns on 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.

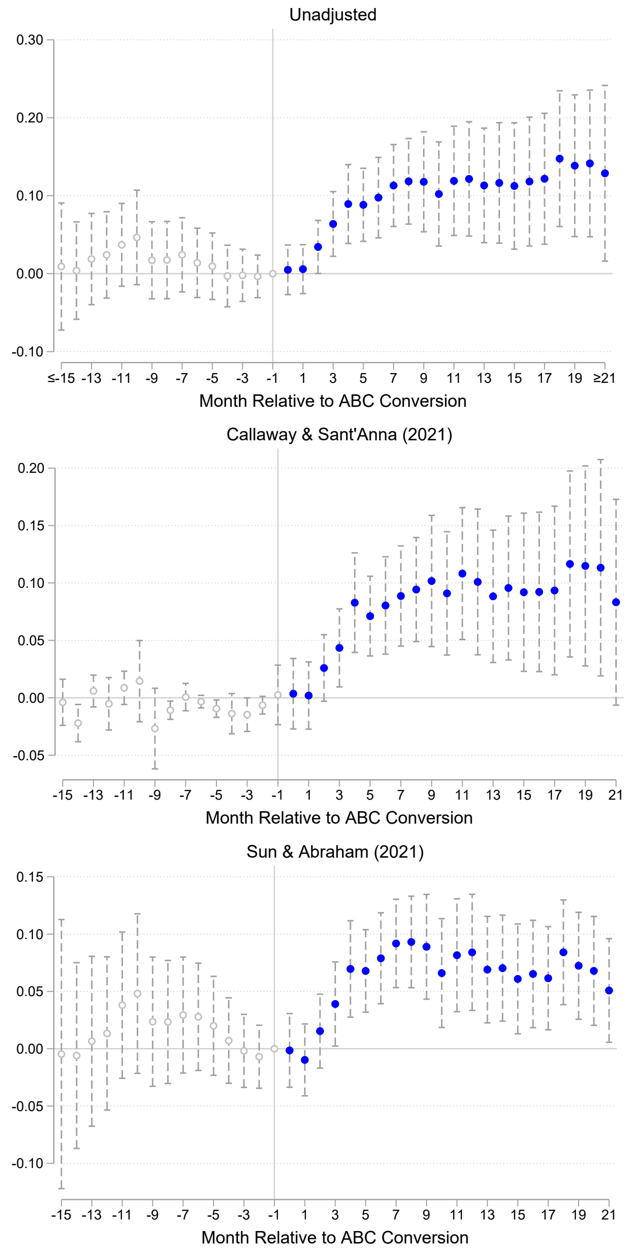


Figure D2: Dynamic Impacts on the Number of Consumers

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.

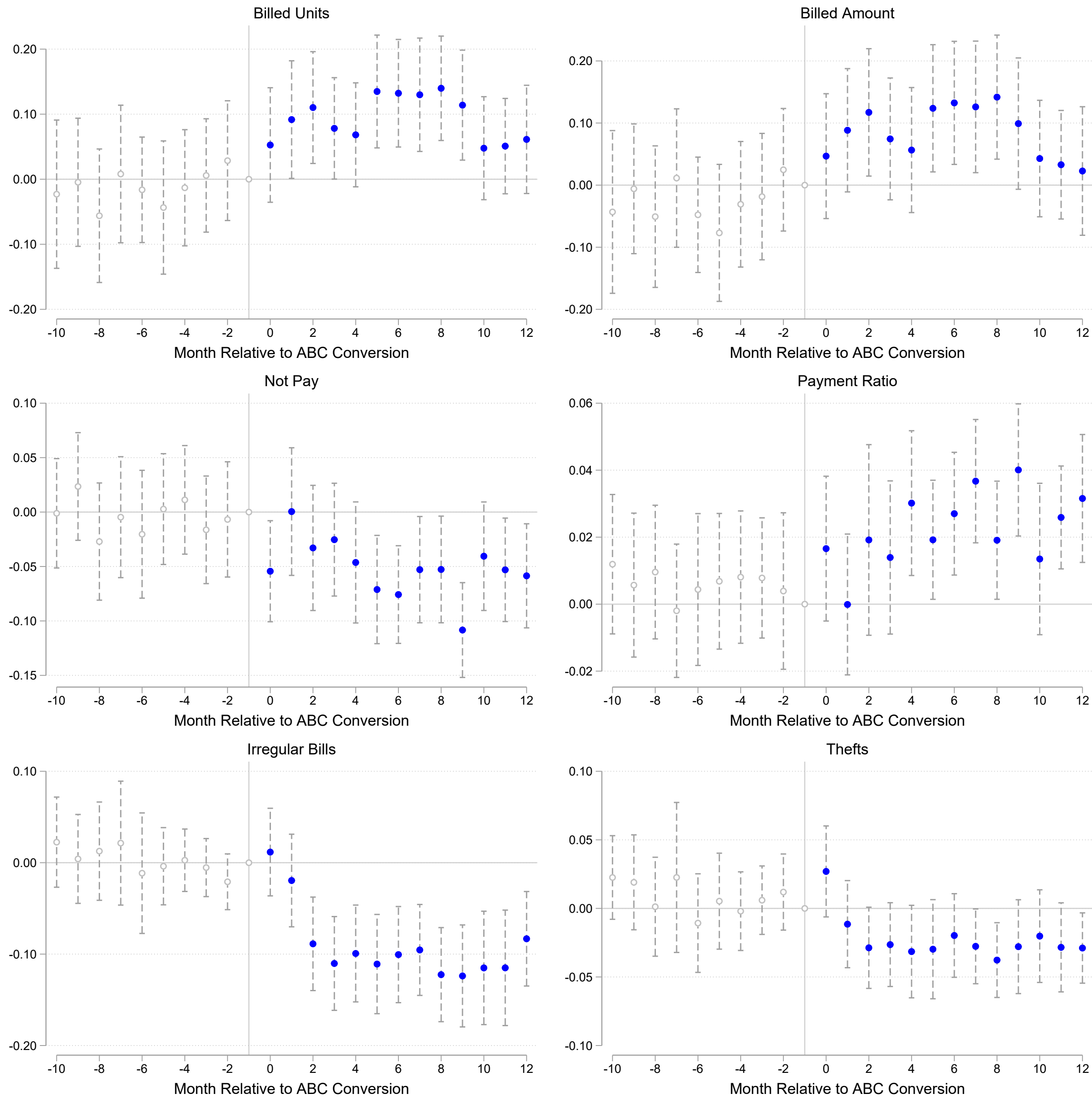


Figure D3: Dynamic Impacts on Customer Behavior

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 are thefts in that month. All regressions include customer, month, and PMT-by-month-of-year fixed effects. Standard errors are clustered at the PMT level.

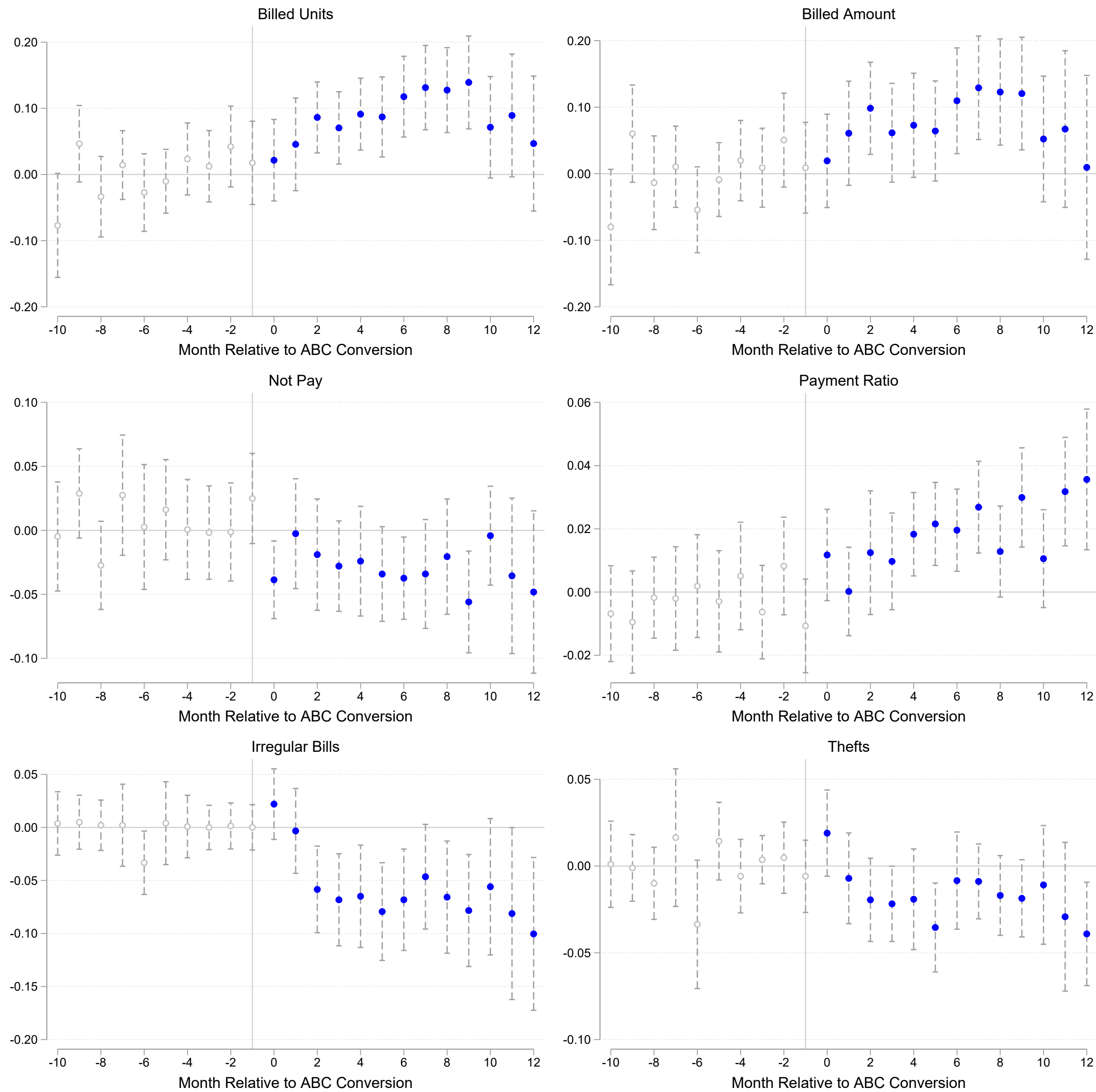


Figure D4: Dynamic Impacts on Customer Behavior – Callaway and Sant'Anna (2021)

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 PMT-by-month-of-year fixed effects. Standard errors are clustered at the PMT level.

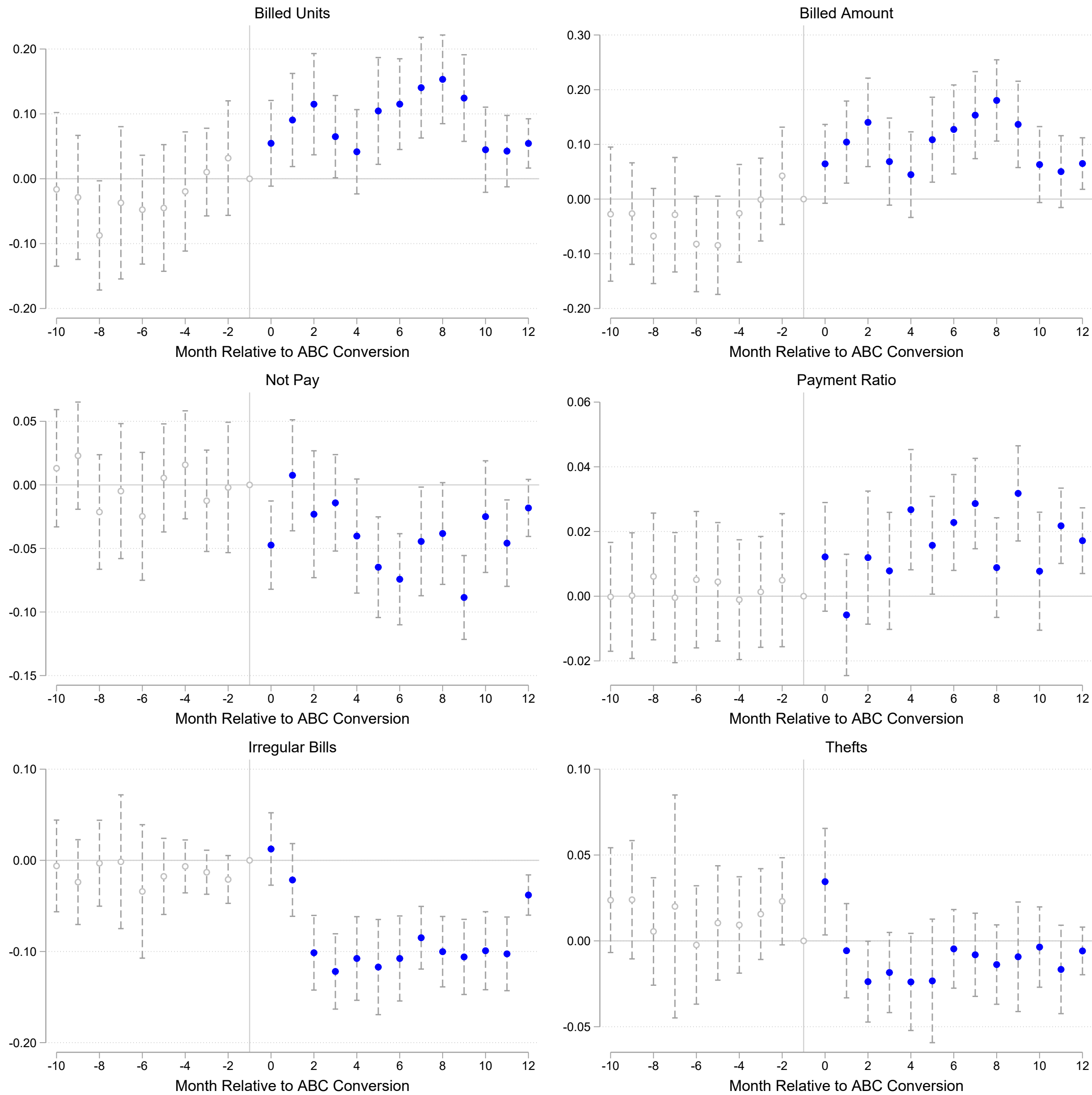


Figure D5: Dynamic Impacts on Customer Behavior – Sun and Abraham (2021)

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 PMT-by-month-of-year fixed effects. Standard errors are clustered at the PMT level.

Table D1: 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 D2: 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 D3: ABC Impact 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 replicate 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 D4: Nonlinearity in Impacts of ABCs

	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 PMTs with ABCs installed divided by the number of total PMTs 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 D5: Robustness Checks of Impacts of ABCs on Losses and Revenue Recovery

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

Notes: Data are at the feeder-line level. The coefficient estimate in each cell is from a separate regression. In Panel A, 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. In Panel B, we address the concern on 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 C, we only keep the feeder-lines with at least 100 m, 300 m, or 500 m distance from their nearest neighbors. In Panel D, 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 E, 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). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

E 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.

E1 ABC Costs to the Utility

We assume the costs of ABCs are all upfront and therefore borne in year 0. We create four cost scenarios based on costs provided by KE, providing us with bounds on the overall costs of ABCs. As a lower bound, we include the costs of ABC materials alone (Scenario 1) and ABCs materials and labor together (Scenario 2) per PMT. To include only material costs (and not labor) in the lowest-bound scenario cost estimate is not completely unrealistic; given that distribution system wires regularly need to be replaced even in the absence of the upgrade to ABCs, we can assume that technical work on the distribution system would still be required and therefore labor expenses are not specific to the infrastructure upgrade.

As upper-bound calculations of the costs of converting to ABCs, we use the cost of ABCs per PMT converted in high-loss areas, both with and without labor included, which are Scenarios 3 and 4, respectively. To put these costs into units comparable to the benefits, we divide the costs per PMT by the average number of consumers per PMT, with an average of 200 consumers per PMT in our dataset. The resulting costs by scenario are in Table E1.

Table E1: Costs to the Utility for ABC Conversion, per Consumer

Scenario	Explanation	Cost per Customer (PKR)
1	Costs: ABC materials alone	16,389
2	Costs: ABC materials and labor	20,487
3	Costs: ABC materials in high-loss areas	24,916
4	Costs: ABC materials and labor in high-loss areas	33,630

Notes: Calculations based on cost data from KE.

E2 Benefits to Utility

To estimate the benefits to KE, we use the change in customer payments to KE following the conversion to ABCs. We use 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 a per-consumer benefit to the utility of 5,729 PKR per year.

We assume a ten-year life span for the ABCs and that the annual benefits are constant over these ten years. Globally, the life span of ABCs is expected to be between 15 to 20 years. However, based on conversations with the electricity utility, we understand that the ABCs have a shorter life span (approximately ten years) when installed in Pakistan, due to the local conditions. For this reason, we use the assumption of a ten-year life span in our calculations.

Benefits could potentially decrease over time; however, we argue that our numbers here still 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 a range of benefits using discount rates of 8%, 10%, and 12%. Results are in Table E2.

Table E2: Discounted Benefits to the Utility from ABC Conversion

Discount Rate	Per-Customer Benefits (PKR)
8%	56,252.73
10%	48,778.12
12%	42,795.91

Notes: Calculations assume a ten-year life span for ABCs installed in Karachi and constant benefit over those ten years.

E3 Comparing Costs to Benefits by Cost Scenario and Discount Rate

Table E3: Net Present Value: Costs versus Benefits of ABC Conversion

	ABC Cost Scenarios			
Discount Rate	1	2	3	4
8%	39,863	35,766	31,337	22,622
10%	32,389	28,291	23,863	15,148
12%	26,407	22,309	17,880	9,166

Notes: All values are in PKR per customer.

We provide cost-benefit comparisons for the four cost scenarios and the benefits calculated with the three different discount rates. Results are presented in Table E3.

F 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).

F1 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.

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).

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.

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.

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

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 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.

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

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.

F2 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.

We use these calculations to estimate the change in the CO_2 emissions from electricity

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 8 of the paper.

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 10.

We know from Table 9 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 F1.

We see in Table 10 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: 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 9 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 F).

Table F8: 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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