

ONLINE APPENDIX

Down to the Wire: Leveraging Technology to Improve Electric Utility Cost Recovery

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A Background on Electricity Distribution

A1 Electricity Distribution and Load Shedding

Load shedding is a type of disruption in the distribution of electricity that is not uncommon in many low and lower-middle income countries. When load shedding occurs in a particular area there is no electricity being delivered to that location (e.g., along particular feeder lines of the distribution system).³⁸ Load shedding can be planned (and potentially announced to the utility's customers before the disruption begins) or unplanned (and therefore also unannounced).

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

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

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

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

³⁸Disruptions in electricity services due to load shedding are different than unplanned outages that occur due to breakage within transmission and distribution systems.

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

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

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

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

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

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

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

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

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

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

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

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

A2 Distribution Infrastructure

The [International Energy Agency \(2020\)](#) expects that between 2020 and 2030, 16 million kilometers of existing electricity distribution lines need to be *replaced*, with approximately 60% of these replacement needs located in low and lower-middle income countries. This will require vast financial investments by distribution companies worldwide; and this does not even include the investments needed for *newly-constructed* distribution lines in settings that are being electrified for the first time in efforts to meet the Sustainable Development Goals.³⁹ Taken together, substantial investments in distribution infrastructure are expected in the near future. Further, distribution network investments are costly, not just in monetary terms but also in terms of time costs. Lower voltage distribution projects typically require 4-7 years to complete ([International Energy Agency, 2022](#)). Costs vary based on the quality and materials used in the components of the distribution network.

³⁹Sustainable Development Goal 7 calls to “ensure access to affordable, reliable, sustainable and modern energy for all.” As of 2020, 733 million people around the world still were without electricity ([United Nations, 2022](#)).

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

i Low-cost Infrastructure

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

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

ii Technical Background and Historical Use of ABCs

Starting in the early 1970s, electricity distribution companies began installing aerial insulated and covered wires and cables within their distribution systems to overcome problems with bare wires. Broadly-speaking, “covered conductor” is the term used to refer to conductors with “an internal semiconducting layer and external insulating UV resistant layers to provide incidental contact protection”, and this covering differentiates the conductor from a bare wire conductor.⁴⁰ Aerial Bundled Cables (ABCs), one type of commonly used covered conductor, are twisted and tightly bundled insulated low voltage

⁴⁰Other terms used for “covered conductors” include “insulated conductor” and “coated conductor” ([Pacific Gas and Electric Company, 2021](#)).

cables ([Pacific Gas and Electric Company, 2021](#)).⁴¹ When introduced to electricity distribution systems in the late 1900s, ABCs were considered quite revolutionary; upon installation in Australia in the early 1980's, ABCs were hailed as "the biggest step forward in overhead distribution line practice in 50 years" ([Williamson et al., 1989](#)).

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

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

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

iii ABCs to Reduce Unbilled Consumption

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

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

⁴¹Depending on the setting, ABCs refer to aerial bundled cables, aerial bunched cables, aerial bunch conductors, and aerial bundled conductors. We will use ABCs to refer to all of these.

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

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

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

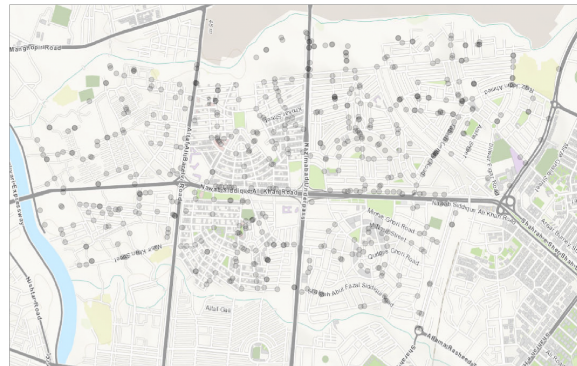
iv Cable Installation in Pakistan

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

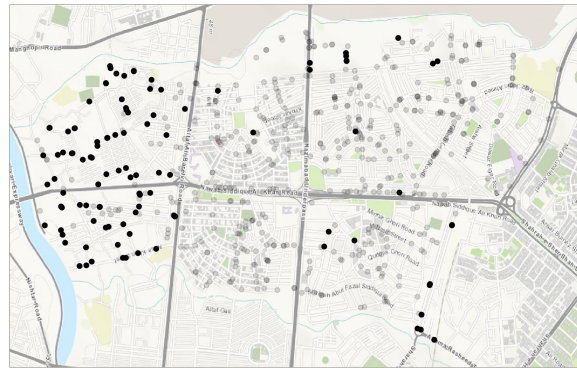
- The Express Tribune. September 07, 2015. "Against tampering: Locals to have theft-resistant electricity cables." Article discussed how the Peshawar Electric Supply Company (PESCO) was replacing old wires with ABCs in an effort to reduce electricity theft. <https://tribune.com.pk/story/951944/against-tampering-locals-to-have-theft-resistant-electricity-cables>
- Such TV. November 24, 2018. "New system being introduced to stop power theft: Omar Ayub." In a television interview, Pakistan's Minister of Energy explained that ABC installation would help control electricity theft and announce plans for an Asian Development Bank funded effort to install ABCs within the distribution network of IESCO, PESCO, and LESCO. <https://www.suchtv.pk/pakistan/general/item/77702-new-system-being-introduced-to-stop-power-theft-omar-ayub.html>

- Pakistan Today. July 27, 2020. "Segmented load-shedding in line with National Power Policy: K-Electric." The article described Karachi Electric's efforts to reduce electricity theft through the installation of ABCs. <https://profit.pakistantoday.com.pk/2020/07/27/segmented-load-shedding-in-line-with-national-power-policy-k-electric/>
- Business Recorder. November 30, 2020. "K-Electric to invest \$1.5 billion in energy infrastructure." Article reports that the utility already invested 55 billion rupees into its distribution network in FY 2020, converting to ABCs and "significantly reducing transmission and distribution losses, and load shedding." <https://www.brecorder.com/news/40036286>
- The Daily Times. December 19, 2020. "K-Electric requests consumers' understanding as it conducts annual preventive maintenance." Article reported that installation of ABCs is a regular part of Karachi Electric's work to upgrade the network and reduce illegal kundas in Karachi. <https://dailytimes.com.pk/703407/k-electric-requests-consumers-understanding-as-it-conducts-annual-preventive-maintenance/>
- The News International. November 23, 2022. "KE says transmission, distribution losses reduced to 15pc in FY22." Article reported on discussion of Karachi Electric's Chief Financial Officer and the company's efforts "to enhance its infrastructure and continue efforts to reduce distribution losses by rolling out aerial bundled cables on its network." <https://www.thenews.com.pk/print/1012680-ke-says-transmission-distribution-losses-reduced-to-15pc-in-fy22>

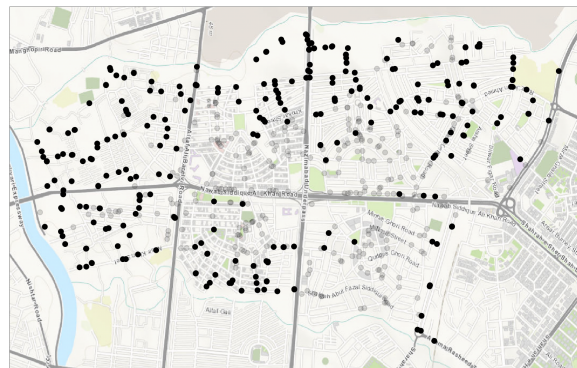
B Maps



(a) 2016m6



(b) 2018m12

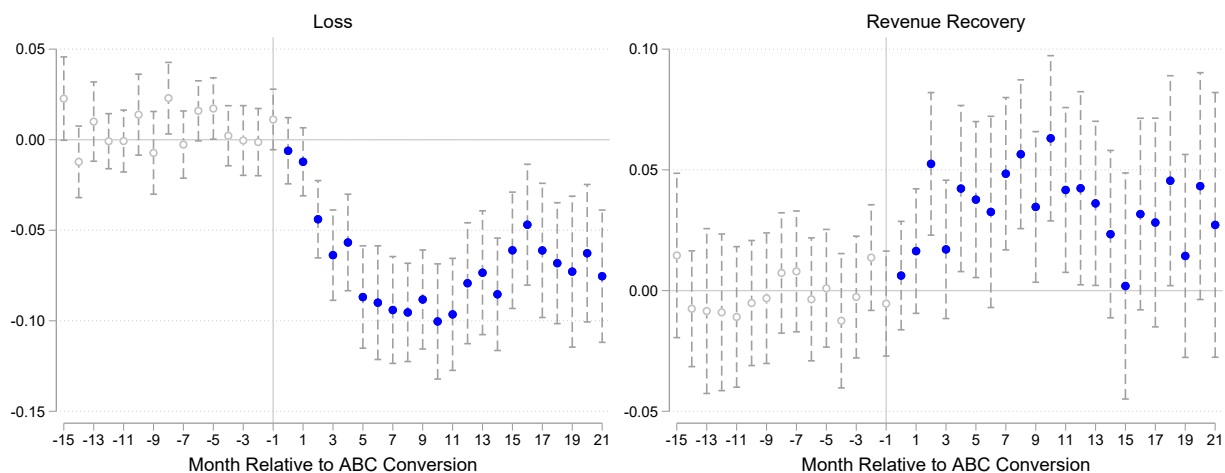


(c) 2020m12

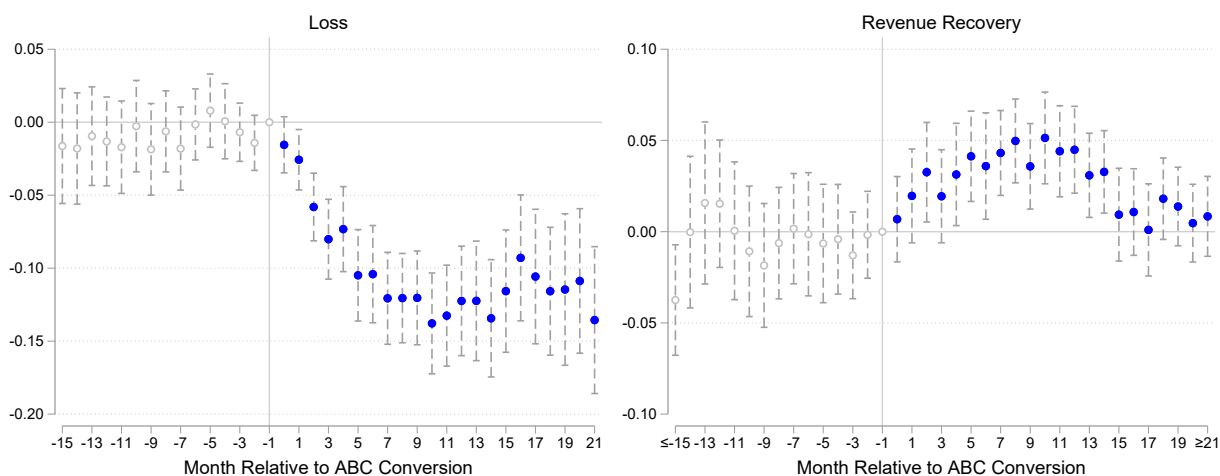
Figure B1: Example of Theft-Resistant Cable Installation at Transformers

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

C Additional Figures and Tables



(a) Adjusted Following [Callaway and Sant'Anna \(2021\)](#)



(b) Adjusted Following [Sun and Abraham \(2021\)](#)

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

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

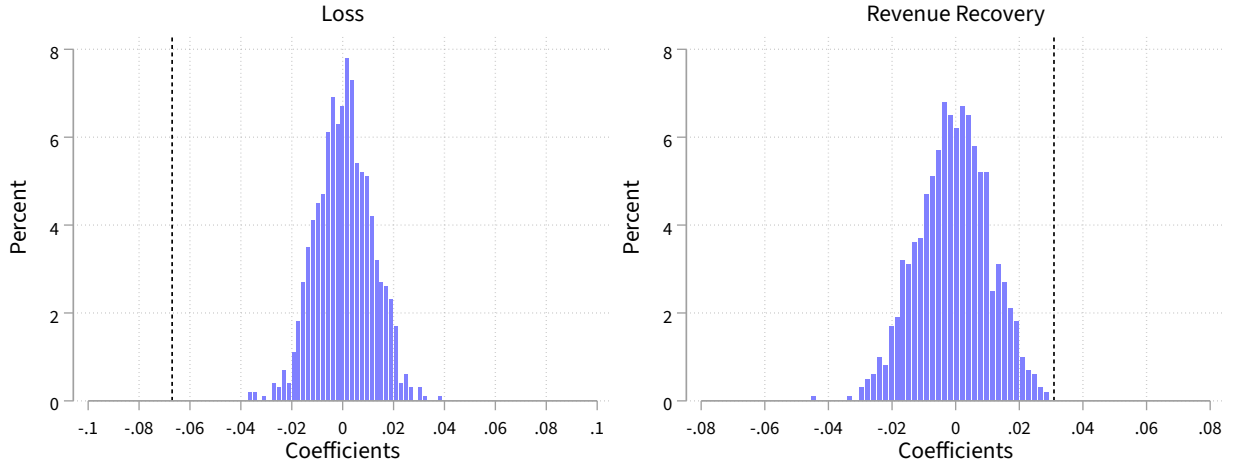


Figure C2: Placebo Tests with High-Loss Feeder Lines

Notes: The figure plots the distribution of coefficient estimates from the placebo test. For these analyses, we restrict our sample to feeder lines that belong to the high-loss category at the baseline. We first shuffle ABC installation across these feeder lines 1000 times. For each pseudo ABC installation status, we estimate the impacts on losses and revenue recovery. The blue bars show the histogram of the coefficients for the ABC indicator. The vertical dashed black lines represent the estimates based on the actual ABC installation status.

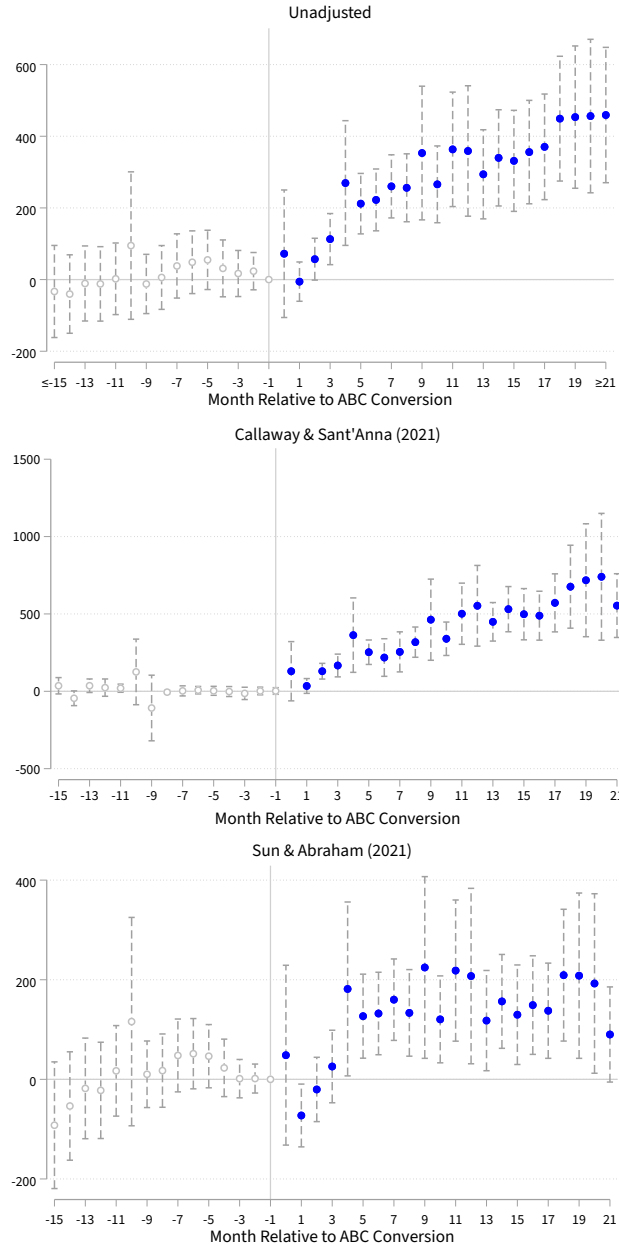


Figure C3: Dynamic Impacts on the Number of Consumers

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.

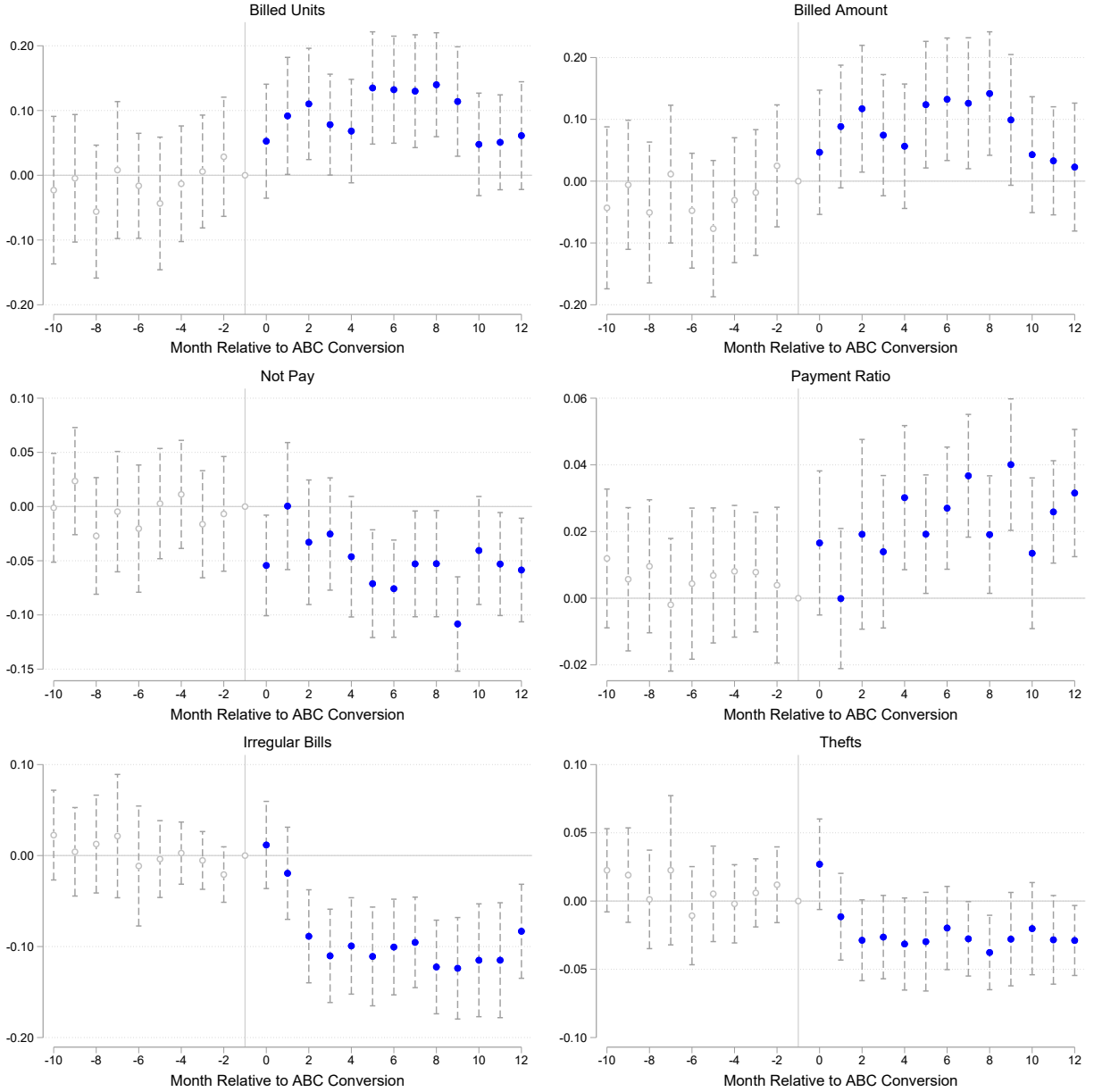


Figure C4: Dynamic Impacts on Customer Behavior

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

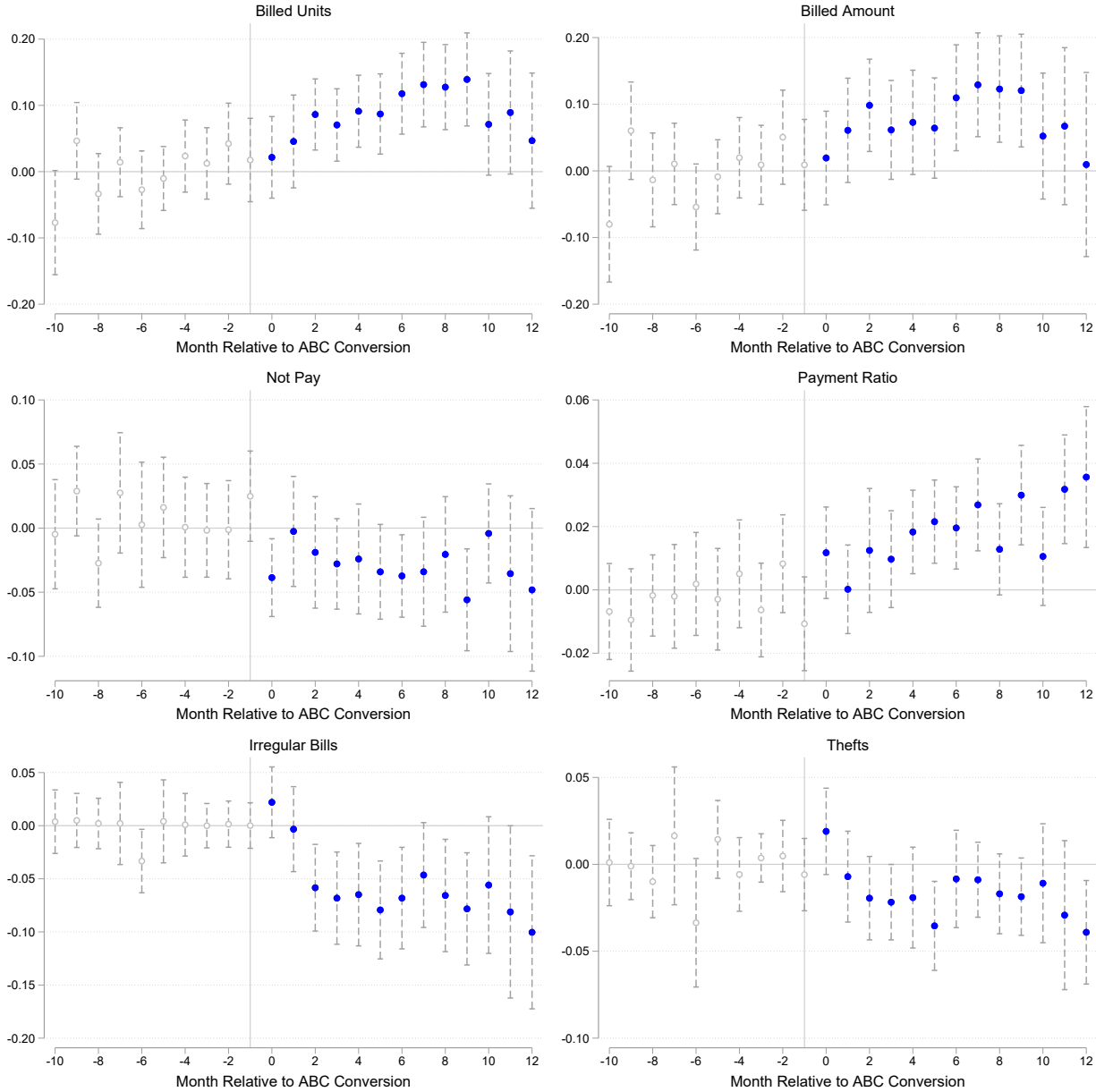


Figure C5: Dynamic Impacts on Customer Behavior – Callaway and Sant’Anna (2021)

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

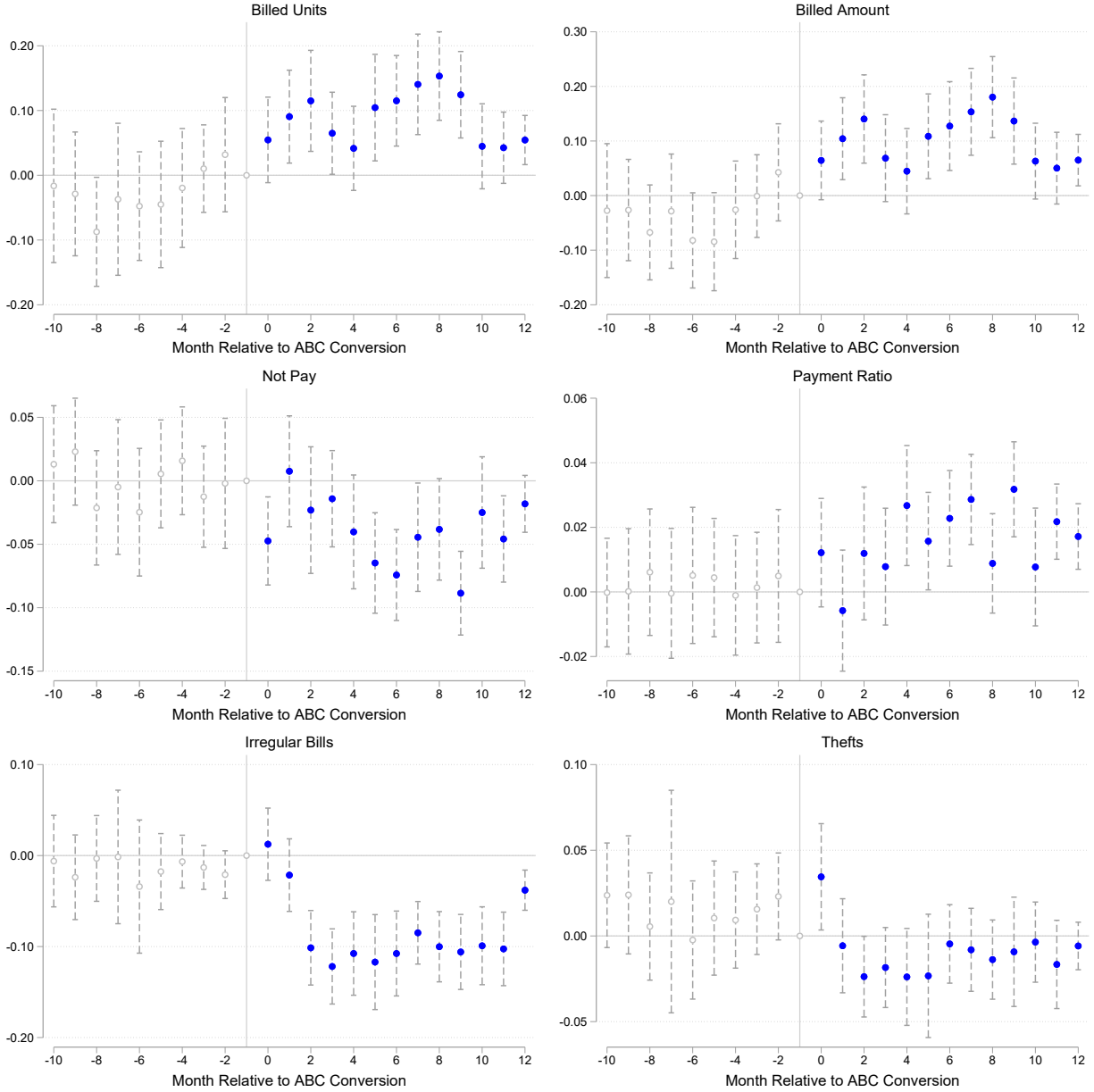


Figure C6: Dynamic Impacts on Customer Behavior – Sun and Abraham (2021)

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

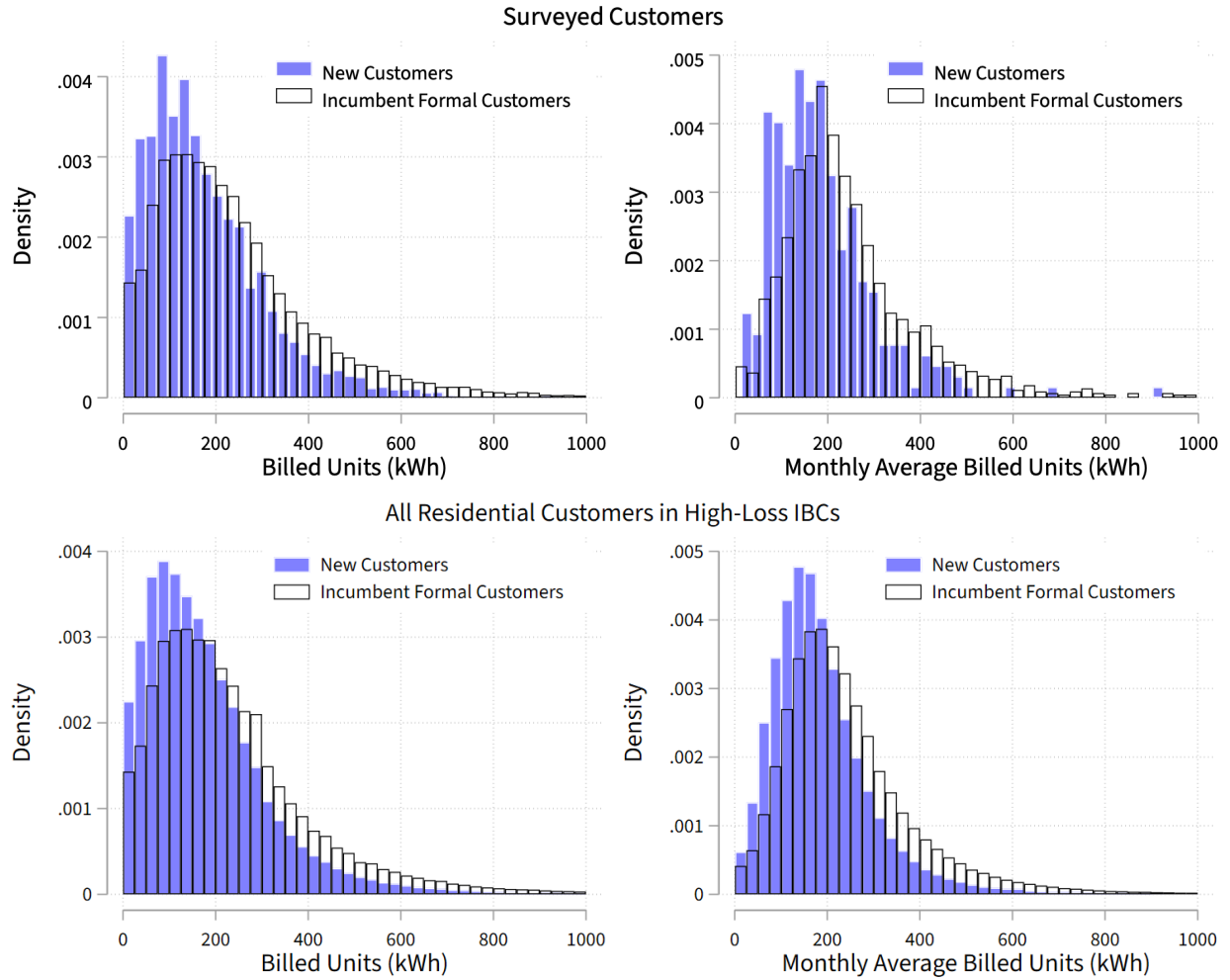


Figure C7: Distribution of Billed Units by Customer Type

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

Table C1: Summary Statistics of Feeder-Line Characteristics

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

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

Table C2: Summary Statistics of General Household Characteristics

Variable	Mean	SD	Min	Max
<i><u>Household Characteristics</u></i>				
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
<i><u>House Characteristics</u></i>				
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
<i><u>Connectivity</u></i>				
% Cell Phone	0.60	0.49	0	1
% Mobile Internet	0.60	0.49	0	1
<i><u>Expenditures</u></i>				
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
<i><u>Asset Ownership and Financial Accounts</u></i>				
% Own Vehicles	0.04	0.19	0	1
% Own Motorcycles	0.59	0.49	0	1
% Own Land	0.05	0.22	0	1
% Financial Account	0.32	0.47	0	1

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

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

Variable	Mean	SD	Min	Max
<i>Electricity Connection Details</i>				
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
<i>Lighting Sources</i>				
% 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
<i>Electricity Service Quality</i>				
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
<i>Appliance Ownership</i>				
% 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
<i>Light Bulb Types</i>				
% Use Incandescent	0.01	0.07	0	1
% Use CFLs	0.26	0.44	0	1
% Use LEDs	0.84	0.36	0	1

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

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

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

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

Table C5: Nonlinear Effects of Theft-Resistant Cables

	Monthly		Quarterly	
	Loss (1)	Revenue Recovery (2)	Loss (3)	Revenue Recovery (4)
ABC Ratio	−0.159*** (0.030)	0.176*** (0.039)	−0.130*** (0.035)	0.185*** (0.041)
ABC Ratio ²	−0.019 (0.032)	−0.092** (0.042)	−0.048 (0.037)	−0.086** (0.043)
Control Mean	0.229	0.828	0.210	0.855
Observations	47,575	37,353	17,626	14,664
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓		
IBC-Quarter FE			✓	✓

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

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

	Monthly		Quarterly	
	Loss (1)	Revenue Recovery (2)	Loss (3)	Revenue Recovery (4)
ABC	-0.024* (0.014)	-0.029*** (0.010)	-0.019 (0.014)	-0.006 (0.009)
ABC × Medium Loss	-0.064*** (0.016)		-0.061*** (0.017)	
ABC × High Loss	-0.135*** (0.030)		-0.143*** (0.032)	
ABC × Medium Revenue Recovery		0.102*** (0.014)		0.083*** (0.013)
ABC × Low Revenue Recovery		0.184*** (0.022)		0.164*** (0.025)
Control Mean	0.230	0.830	0.212	0.858
Observations	43,041	35,897	15,914	14,008
Feeder FE	✓	✓	✓	✓
IBC-Month FE	✓	✓		
IBC-Quarter FE			✓	✓

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

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

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

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

Table C8: Robustness Checks: CSR Camps

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

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

Table C9: Robustness Checks: Old Meter Replacements

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

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

Table C10: The Effects of Old Meter Replacements

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

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

Table C11: Robustness Checks: Project Sarbulandi

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

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

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

VARIABLES	Total (1)	Agricultural (2)	Bulk (3)	Commercial (4)	Industry (5)	Residential (6)
<i>A. Log Measure</i>						
ABC	0.066*** (0.022)	-0.002 (0.015)	-0.003 (0.005)	-0.018 (0.028)	-0.010 (0.030)	0.065** (0.026)
<i>B. Raw Level Winsorized at the 99th Percentile</i>						
ABC	169.041*** (40.694)	-0.041 (0.079)	-0.005 (0.007)	2.333 (5.568)	-0.484 (0.745)	166.851*** (37.175)
<i>C. Inverse Hyperbolic Sine</i>						
ABC	0.065*** (0.022)	-0.002 (0.019)	-0.004 (0.006)	-0.023 (0.029)	-0.009 (0.035)	0.064** (0.028)
<i>D. Log Measure</i>						
ABC Ratio	0.140*** (0.032)	0.004 (0.007)	-0.006 (0.006)	-0.043 (0.043)	-0.018 (0.045)	0.161*** (0.040)
<i>E. Raw Level Winsorized at the 99th Percentile</i>						
ABC Ratio	444.990*** (57.608)	-0.054 (0.080)	-0.009 (0.009)	4.269 (7.389)	-1.325 (1.151)	439.582*** (52.419)
<i>F. Inverse Hyperbolic Sine</i>						
ABC Ratio	0.138*** (0.033)	0.005 (0.009)	-0.008 (0.008)	-0.053 (0.047)	-0.015 (0.052)	0.159*** (0.043)
Outcome Mean	1612.16	1.26	0.09	268.35	11.93	1330.54
Observations	67,602	67,602	67,602	67,602	67,602	67,602

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

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

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

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

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

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

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

Table C15: Quantile Regression Analysis – The Effect of Theft-Resistant Cables on Billed Units

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

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

D Utility Cost-Benefit Calculations

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

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

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

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

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

Scenario	Costs Included in Scenario	Cost per Customer	
		(PKR)	(USD)
1	ABC materials alone	16,389	109.3
2	ABC materials + labor	20,487	136.6
3	ABC materials + old meter replacement	24,916	166.1
4	ABC materials + old meter replacement + labor	33,631	224.2

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

In some cases – but not all – KE replaced the old meters with new meters at the time when ABC conversion occurred. These new meters are the same technology as the old ones that they replaced, just newer (i.e., they are not a more advanced technology, such as prepaid meters or smart meters). The old meters were replaced if they were either

damaged and not properly functioning or – because the ABC wires replace all the bare wires in the distribution system, even those leading directly to the house – it was more efficient for the utility to replace the meter at the same time that the ABC was installed. For these reasons, we create two additional cost scenarios, one in which the old meters are replaced at the time of the ABC conversion (Scenario 3) and one that additionally includes the associated labor costs (Scenario 4). Given KE did not replace all old meters during our study period, we know that Scenarios 3 and 4 are higher than expected for the per customer cost of the ABC installation.

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

D2 Benefits to the Utility

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

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

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

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

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

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

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

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

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

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

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

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

to further understate the true tradeoff for the utility, given our benefits calculations only include the additional billed value collected by the utility.

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

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

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

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

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

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

E Theft Reduction and Consumer Surplus

E1 A Model of Cables' Impacts on Consumers

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

i 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 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.⁴² 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

⁴²For ease of exposition, we simplify the scenario to these two consumer types. Although a formal consumer could, on occasion, manipulate their meter or also use a kunda, so as not to pay the full cost of their electricity services consumed, we note that mathematically it would be equivalent to "split" such a consumer into two distinct consumers, one with a "formal demand" and one with a "kunda demand." Intuitively, this is similar to the construction of a demand curve with different willingness to pay for additional units of a product under the law of diminishing marginal utility.

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

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

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

ii 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.

iii Formal Consumers: Change in Consumer Surplus

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

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

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

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

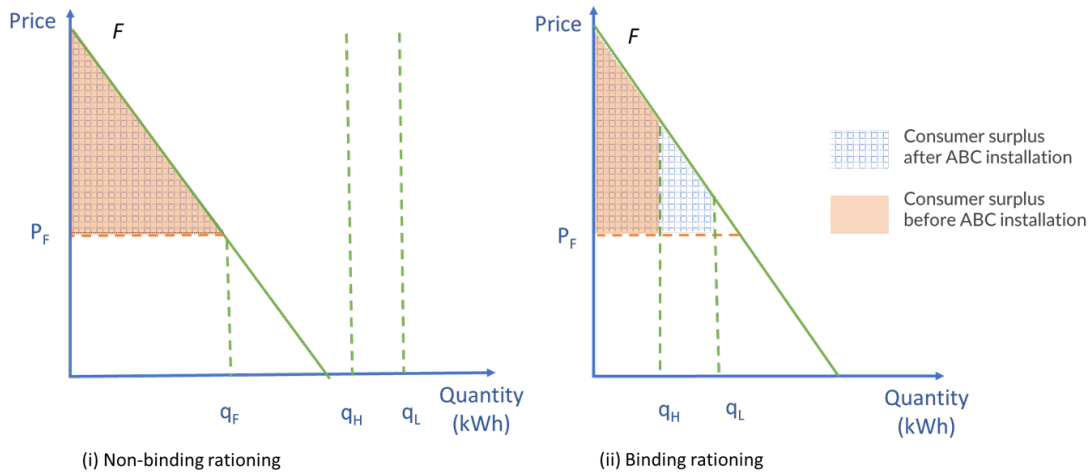


Figure E1: Consumer Surplus of Formal Consumers

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

iv Kunda Users: Change in Consumer Surplus

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

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

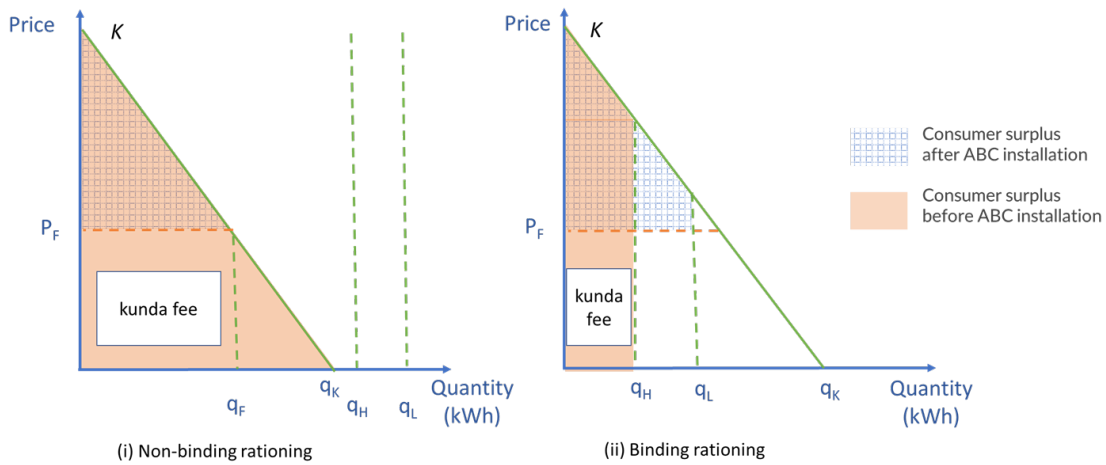


Figure E2: Consumer Surplus of Kunda Users

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

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

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

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

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

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

E2 Consumer Surplus Calculation

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

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

To measure the change in consumer surplus, we estimate price elasticities of electricity demand. We leverage the monthly feeder-level data on electricity sent out, bill payment, and the number of customers to conduct the estimation. For each feeder-line, we calculate the average electricity consumption per consumer (y_{it}) as the total consumption divided by the average number of customers in the period after ABC installation.⁴³

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).⁴⁴

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

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

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

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

⁴³The 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.

⁴⁴As kunda pricing is considered a lump-sum transfer, we ignore kunda payments for the purposes of calculating the average price.

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

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

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

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

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

Kunda Fee (1)	Δ CS per Consumer (2)	Δ CS Total (3)	Δ Kunda Revenue (4)	Δ Subsidy (5)
0	−682	−473,548,704	0	−133,894,840
750	−607	−421,442,912	−52,105,772	−133,894,840
1,500	−532	−369,337,152	−104,211,544	−133,894,840
2,000	−482	−334,599,968	−138,948,720	−133,894,840
2,500	−432	−299,862,784	−173,685,904	−133,894,840
3,500	−332	−230,388,416	−243,160,272	−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 (Δ CS) 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). Δ Subsidy is measured by the change in government subsidies for electricity. Details for the calculation are described in Section E2.

F Implications for Climate Change Mitigation

Ex ante, the implications of the theft-resistant cable installation for electricity generation and, therefore CO₂ emissions, are not obvious. If anything, our results suggest that emissions may increase as a result of infrastructure upgrades: the cables led to an increase in both the total number of utility customers and billed units (kWh) per customer, which together suggest an increase in electricity supplied and therefore electricity generated. In a setting such as Pakistan, where 62% of electricity generation is via fossil fuels ([NEPRA, 2021](#)), an absolute increase in electricity generation likely means an increase in CO₂ emissions.

F1 Estimating Reductions in Emissions

In this section, we explore the implications of the infrastructure upgrade for climate change mitigation through a multi-step process. First, we estimate the impacts of theft-resistant cables on a proxy for electricity generation. Then, we calculate the marginal changes in CO₂ emissions per kWh change in electricity generated. Third, using the results of the prior two steps, we perform back-of-the-envelope calculations to estimate the cables' influence on CO₂ emissions. Lastly, to provide some perspective, we compare these estimates to the CO₂ emissions from KE's annual generation.

For the first step, given that generation occurs at a higher level than the intervention, we use the quantity of electricity "sent out" (kWh) to a feeder-line per month (i.e., the quantity delivered to a feeder-line) as a proxy for generation per feeder-line.⁴⁵ To estimate the impact of the cables on electricity generation, we run regressions akin to those described in Equation 1, but with the quantity sent out as the outcome variable. Results in Table F7 show that theft-resistant cables led to a decrease in generation of 97,213.3 kWh per feeder-line per month (column 1). Using the inverse hyperbolic sine transformation of the quantity sent out, the intervention led to a 10.2% decrease in generation per feeder-line per month (column 2). These results indicate that the cables reduced the total electricity delivered and, therefore, the quantity generated.

To translate these generation reductions per month into avoided CO₂ emissions, we perform calculations of the estimated reduction in CO₂ emissions per kWh reduction of electricity generated, specific to Pakistan's generation mix. Details of these calculations

⁴⁵Electricity sent out includes billed consumption, unbilled consumption, and technical losses. A reduction in technical losses can be considered a pure welfare gain as CO₂ emissions are averted but consumption is not reduced. However, a reduction in billed or unbilled consumption might have welfare consequences for consumers, which we are unable to capture in this calculation.

are in Appendix F3. Broadly speaking, we create a mix of fuels that would most likely be used to respond to changes in demand. This “responsive mix” consists mostly of generation attributed to fossil fuels, as these technologically allow for relatively easier changes in production, compared with other sources. Our calculations indicate that the reduction in CO₂ per kWh reduction of electricity services consumed is 0.76 kg CO₂/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 CO₂/kWh and 1.06 kg CO₂/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 CO₂ emissions per change in electricity generated by generation fuel type, we compare those calculations to Pakistan’s annual CO₂ emissions to put those numbers in perspective. Results are in Table F8. In column 1, we present the result of multiplying each of these estimated changes in CO₂ per kWh change in generation by fuel type times the estimated reduction in generation: 97,213.3 kWh per feeder-line per month (from column 1 of Table F7). This provides us with a range of estimated reductions in CO₂ 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 CO₂ emissions from KE’s annual generation (column 4). This reduction in CO₂ emissions is non-trivial, equal to roughly 1.67% to 4.26% of KE’s annual emissions due to generation.

F2 Comparing Theft-Resistant Cables with Other Interventions

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

We perform back-of-the-envelope calculations for the electricity savings that would occur if a household replaced three incandescent light bulbs with more efficient LED light

bulbs. We perform these calculations based on [Carranza and Meeks \(2021\)](#), which reports estimated reductions in electricity consumption due to a randomized energy efficient light bulb intervention in Kyrgyzstan. First, we calculate the power reduction (kW) per household from making this switch to LEDs.⁴⁶ We then use that estimated reduction to calculate the expected reduction in billed electricity (kWh) per month (Appendix Table F9). Calculations by season place the per-household kWh reduction due to switching three incandescent light bulbs to LEDs at between 24.3 and 44.55 kWh per month, which is just below the 57.7 kWh per month of the theft-resistant cable-induced reduction calculated per consumer. Therefore, the reduction from theft-resistant cables is equivalent to that of shifting to more efficient lighting.

F3 Calculations: Reductions in CO₂ Emissions

In this section, we detail the steps involved in calculations pertaining to CO₂ emissions and the impacts of ABCs on them. First, we calculate the CO₂ emissions produced for all electricity generated and delivered to the service area covered by KE. Second, we estimate the reduction in CO₂ per kWh reduction of electricity services consumed, in order to estimate the reduction in CO₂ emissions resulting from the installation of ABCs. Lastly, we use these two calculations together to compare the CO₂ 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](#)).

i CO₂ Emissions for Electricity Purchased by Karachi Electric

We first calculate the CO₂ emissions for all units purchased for KE's service territory. NEPRA's report provides information on KE's system generation, as well as the purchases KE makes from the Central Power Purchasing Agency (CPPA-G). As shown in Table F1, the generation mix differs across the two sources.

In FY 2020-21, KE procured a total of 19,486 GWh. This consisted of electricity generated within the KE system (13,116 GWh), as well as outside purchases from CPPA-G (6,118 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 CO₂ per MWh. We

⁴⁶We assume households would replace a 100 W incandescent bulb with a 100 W equivalent LED bulb. Actual wattage listed for LEDs is typically 10 W for a 100 W equivalent bulb. Therefore for each incandescent bulb replaced by an LED, there is a reduction of 90 W (100 W – 10 W). If the household has three light bulbs and replaces all of them, the power reduction is 270 W or 0.27 kW.

Table F1: Generation Mix for Pakistan, 2021

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

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

assume that liquefied natural gas is same as natural gas throughout the calculations. We multiply the average heat rate for the (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	12	97	1,170

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

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

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

Table F3: Emissions from KE System Electricity Generation

Generation Fuel	Contribution to KE (GWh)	Contribution to KE (MWh)	Emissions Intensity (kg CO ₂ /MWh)	Emissions Total by Fuel (kg CO ₂)
Natural Gas	8,198.59	8,198,590	460	3,771,351,400
RFO	4,265.00	4,265,000	1060	4,520,900,000
Coal	453.00	453,000	1170	530,010,000
Sum				8,822,261,400

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

Table F4: CPPA-G Generation

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

We know from the NEPRA report (NEPRA, 2021) that KE purchased 6,118 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 CO₂ emissions from the electricity units that KE purchased from CPPA-G. We multiply the proportions in the far right column of Table F4 with 6,118 GWh and get the results shown in Table F5.

We next sum the emissions from the electricity units purchased from KE (8,822,261,400 kg CO₂) in Table F3 and the emissions from the electricity units purchased from CPPA-G (2,748,566,671 kg CO₂) in Table F5. We then convert this total of 11,570,828,071 kg CO₂ to US tons, resulting in an estimated 12,754,639 tons of CO₂ per year from the generation of the electricity units purchased by KE.

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

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

ii CO₂ 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:

$$\text{Natural gas: } (3420.59 + 4778) / (3420.59 + 4778 + 4265 + 453) = 0.635 \quad (\text{A1})$$

$$\text{RFO: } 4265 / 12,916.59 = 0.330 \quad (\text{A2})$$

$$\text{Coal: } 453 / 12,916.59 = 0.035 \quad (\text{A3})$$

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 CO₂ 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:

$$= (460 \times 63.5\%) + (1,060 \times 33\%) + (1,170 \times 3.5\%) \quad (\text{A4})$$

$$= 6830 \text{ kgCO}_2/\text{MWh} \quad (\text{A5})$$

$$= 0.68 \text{ kgCO}_2/\text{kWh}. \quad (\text{A6})$$

This calculation provides our basic estimation of the reduction in CO₂ per kWh reduction of electricity services consumed: 0.68 kg CO₂/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 CO₂ per kWh reduction of electricity services consumed, we can alternatively assume that the marginal generation is either strictly natural gas (the least carbon intensive of the three fuels) or RFO (the most carbon intensive of the three fuels). This provides us with the range of estimates in Table F6.

Table F6: Change in CO₂ 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	0.68
RFO	1.06
Coal	1.17

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

We use these calculations to estimate the change in the CO₂ emissions from electricity generated, depending on which of these fuels is the marginal fuel: natural gas, residual fuel oil, coal, or the responsive blend calculated earlier. We present these calculations in Table F8.

We know from Table F7 that the change in the quantity sent out per feed line as a result of the ABC intervention is -97,213 kWh per month. We multiply that amount by the change in the CO₂ per kWh generated via each fuel, and convert to metric tons of CO₂ per feeder-line per year. To aggregate these avoided CO₂ 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 CO₂ 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 i.

We see in Table F8 that the reduction in CO₂ emissions resulting from the approxi-

mately 400 high-loss feeder-lines being converted to ABCs, would result in a reduction of CO₂ emissions somewhere between 1.67% and 4.26% of the emissions due to electricity generated for KE.

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

	Quantity Sent Out (kWh per month)	
	Level (1)	IHS (2)
ABC	−97,213.292*** (18,433.656)	−0.102*** (0.023)
Outcome Mean Level	921,096	921,096
Observations	47,575	47,575
Feeder-line FE	✓	✓
IBC-Month FE	✓	✓

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

Table F8: Change in CO₂ Emissions per Change in Electricity Generated

Generation Fuel(s)	Δ in CO ₂ (t CO ₂) / Δ Generation (MWh) (1)	Δ in CO ₂ Emissions per Feeder (tons) (2)	Aggregated: High-Loss Feeders	
			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	-0.68	-793.3	-315,718	2.48%
RFO	-1.06	-1,236.6	-492,148	3.86%
Coal	-1.17	-1,364.9	-543,220	4.26%

Notes: The steps leading to these results are detailed in Appendix F3. Column 1 is based on the numbers reported in Table F6. Column 2 is calculated by multiplying the values in column 1 by -97,213 kWh per month, which is the reduction estimated in Table F7 as the reduction in quantity sent out to a feeder-line per month as a result of the ABC installation. Column 3 is calculated by multiplying column 2 by 398, based on the utility's 398 high-loss feeder-lines. Column 4 is calculated by dividing column 3 by 12,754,639 tons of CO₂, which was our estimate for the total CO₂ emissions for generating the units of electricity (kWh) that KE purchased per year.

Table F9: Scenarios of Expected Household Reductions in Monthly Electricity Bill, by Season

	Winter	Spring/Fall	Summer
(p) kW Reduction per Household	0.27	0.27	0.27
(q) Average Hours of Bulb Use per Day	5.5	4.5	3
(r) Days in Month	30	30	30
(s) Expected LED Savings per HH 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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