Constrained Cooling: Electricity Infrastructure, Heat, and Household Responses in Pakistan*

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January 15, 2025

Abstract

This paper examines the effects of a utility's efforts to reduce theft and improve cost recovery on customers' ability to adapt to extreme temperatures. We leverage unique monthly data on utility operations and customer electricity bills, enabling us to capture unbilled electricity consumption. Our identification strategy relies on month-to-month variation in temperature and the staggered rollout of theft-resistant cable upgrades in Karachi, Pakistan. We find that unbilled electricity consumption is highly responsive to temperature, reflecting increased reliance on informal connections during hot periods. Although cable upgrades reduce overall electricity usage by curbing illegal connections, their effectiveness diminishes during hotter months, suggesting that households may resort to alternative informal methods to meet persistent cooling needs. Poorer households exhibit "comfort-smoothing" behavior by reducing consumption on moderate days to manage higher bills during extreme heat, whereas wealthier households maintain stable usage patterns. These findings highlight the significant challenges low-income households face in accessing reliable cooling services and underscore the distributional impacts of infrastructure upgrades in a climate-vulnerable, high-loss setting.

Keywords: Electricity, Heat, Infrastructure, Losses
JEL Codes: L94, P48, Q40, Q56

*We are grateful to Karachi Electric for data provision and many helpful conversations. We thank Ramsha Sajid for excellent research assistance. All errors are our own. This research was generously funded through Duke University Sanford School Pilot Funding and with UK Aid from the UK government under the Applied Research Programme on Energy and Economic Growth (EEG), managed by Oxford Policy Management. All views expressed in the paper and any errors are our own. The views expressed here do not necessarily reflect the UK government's official policies. The research conducted for this paper received IRB approval at Duke University (Protocol: 2022-0052), Lahore University of Management Sciences (Protocol: LUMS-IRB/112120AA-FWA-00019408), and Sewanee: The University of the South (Project: 1927943-1).

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1 Introduction

Global climate change is increasing temperatures and exposing the planet's population to extreme heat. Households and firms may adapt through cooling services (e.g., buying and using air conditioners). Indeed, in high income countries such as the United States, cooling services have played a vital role in mitigating damages from heat (Barreca et al., 2016; Park et al., 2020; Heutel, Miller and Molitor, 2021). As household incomes grow and temperatures increase worldwide, so too has the adoption of air conditioners (Auffhammer, 2014; Davis and Gertler, 2015; Davis, Martinez and Taboada, 2020; Randazzo, Pavanello and De Cian, 2023). Yet billions of people currently live without air conditioners in low and middle income countries that have tropical climates (Biardeau et al., 2020) and future AC adoption in such countries is predicted to be predominantly only amongst the highest income households (Davis et al., 2021).

How are poor households in developing countries responding to extreme heat? Little evidence exists, despite existing evidence suggesting that much of the planet's poorest households must adjust to increasing temperatures without the same tools used to mitigate heat damage in high income countries.[1]

This is a critical research gap. Not only may the poorest households in developing countries have difficulty purchasing air conditioners, there may also be constraints on the intensive margin (i.e., the electricity to power the ACs is costly). This may translate into greater incentive for electricity theft: households owning air conditioners may use informal electricity connections to ensure electricity consumption remains unbilled. Moreover, cooling services require electricity infrastructure and reliable service; however, the electricity sector in many developing countries is prone to low utility cost recovery, insufficient investment in upgrades and modernization, and overloaded infrastructure (Burgess et al., 2020; Carranza and Meeks, 2021). Many utilities are making infrastructure

[1] There is, however, recent research providing evidence as to how firms and their employees may adjust to higher temperatures (see, e.g., Adhvaryu, Kala and Nyshadham, 2020; Somanathan et al., 2021).

investments to alleviate these problems, yet it is uncertain how infrastructure improvements interact with demand for cooling services.

In this paper, we report results from analyses using data from Karachi, Pakistan to make progress on our understanding. Specifically, we ask: how are poor households responding to hot temperatures in terms of their electricity usage? Do infrastructure upgrades that were designed to reduce electricity theft affect electricity usage and losses differently under different temperatures? Is there evidence that the infrastructure improvements affect poor households' adaptation to extreme heat?

Pakistan provides a suitable setting for such a study, with respect to both extreme heat and poverty. The country, which had a population of 216.5 million people as of 2019 (World Bank and ADB, 2021), is classified as lower-middle income by the World Bank.[2] Approximately one-third of households are living in poverty. It is among the 10 countries most negatively impacted by climate disasters (World Bank, 2022). To date, the temperatures observed in Pakistan are among the highest recorded in Asia, with average temperatures in many parts of the country that exceed 30 degrees Celsius for multiple consecutive months (World Bank and ADB, 2021). Heat waves are even worse: for example, in 2022 the country experienced such an extreme heat wave that the mean temperatures in March and April of that year were hotter than any recorded since 1961 (World Meteorological Organization, 2023). Predictions for future temperatures indicate the situation will only grow more dire, with the country expected to experience temperature increases that are higher than the global average (World Bank and ADB, 2021).

Our study occurs in Karachi, which is the largest city in Pakistan and the twelfth largest in the world. Although Karachi is the economic center for the country, it is also the home to millions of people living in poverty, many in informal settlements. There have historically been high non-technical losses due to meter malfunction, thefts, and bill non-payment, particularly in the areas of the city housing the poorest populations.

[2]These classifications are based on calculations of gross national income (GNI) per capita.

To address these issues, the utility serving the city – Karachi Electric (KE), began a cable upgrading starting from 2015 to reduce electricity thefts. Prior research underscored two key points for the paper here. First, the utility's infrastructure upgrade significantly reduced unbilled electricity consumption and, second, our household surveyed in these high loss areas indicated that only 3% of households in these areas of Karachi report owning air conditioners (Ahmad et al., 2024). With these two findings, we embarked to understand how these poor households were responding to high temperatures, given the low reported AC ownership and whether the infrastructure upgrade affected how those households responded.

To complete these analyses, we use a combination of three main datasets. First, we use utility data on feeder-line level outcome measures, including data on losses, revenue recovery, infrastructure damage, and the staggered installation of theft-resistant cables across the city. A notable feature of this dataset is its ability to capture unbilled electricity consumption. Second, we combine consumer-level data from our own household survey conducted with approximately 3,000 utility customers in high loss areas with monthly billing data (for those same 3,000 utility customers) from the utility. Last, we assemble gridded weather information from the ERA5-Land reanalysis data provided by the European Center for Medium-Range Weather Forecasts (ECMWF).

We begin by modeling household decisions regarding the procurement of electricity for cooling services, either through formal connections or illegal means. The model predicts that as temperature rises, more households resort to illegal connections, reducing the effectiveness of theft-resistant cables in mitigating losses. We then conduct two primary empirical analyses using combined datasets. First, we estimate the impact of temperature on various electricity outcomes at the feeder-line and household levels, leveraging plausibly exogenous month-to-month variations in exposure to the distribution of daily temperatures. Second, we assess how cable upgrades influence electricity outcomes under different temperature conditions. The staggered rollout of cable upgrades

depends on pre-determined feeder line losses and utility resource constraints, creating variation across locations and over time. Our identification strategy follows the spirit of a difference-in-differences approach, comparing the electricity consumption under different temperature conditions in treated and non-treated locations before and after cable upgrades.

Our analyses provide several key results. First, based on feeder line level data analyses, we find that both billed and unbilled electricity consumption increase significantly as temperature rises; however, unbilled consumption is considerably more responsive, exhibiting sharper increases during hot days. Supporting evidence indicates that customers may tamper with the distribution system during extreme heat, through practices such as meter tampering or wire puncturing. A more granular analysis of billed consumption among formally contracted households reveals increased electricity bills during hotter months. This effect is particularly pronounced for households that reported owning and frequently using cooling appliances.

Second, at the feeder line level, the installation of theft-resistant cables led to a reduction in total electricity consumption across all temperature bins, which is mainly driven by decreased unbilled consumption with no significant change in billed consumption. These results suggest that higher costs and barriers to illegal connections introduced by cable upgrades may lead to a net reduction in electricity usage especially for poorer households who may have been informally connected. During hotter months, the reduction in unbilled consumption diminishes. We find that reports of intentional wire damage decreased but reports of meter damage increased during hotter months, suggesting that customers may resort to alternative informal methods to meet persistent electricity needs for powering cooling appliances.

Lastly, after cable upgrades, billed consumption of formally contracted customers decreases on moderate days but increases on hot days. The rise in bills during hot periods likely reflects improved billing accuracy due to the elimination of previously accessible

illegal connections. Conversely, the reduction in billed consumption on moderate days suggests that poorer households engage in "comfort-smoothing" behavior, cutting back on discretionary electricity use to manage costs and accommodate higher bills during hotter periods. This behavior is primarily observed among poorer households, whereas wealthier households exhibit no change in consumption on moderate days, likely due to their greater capacity to absorb higher costs.

The paper contributes to the economics literature on heat and adaptation. First, the paper provides evidence on the relationship between temperature and electricity consumption in a lower income setting, complementing the existing evidence on temperature from increasing electricity demand from high and middle-income countries (see, e.g., Auffhammer, Baylis and Hausman, 2017; Li, Pizer and Wu, 2019; McRae, 2023). Next, the analyses contribute to filling a key gap in our understanding as to how poor households in developing countries may mitigate the damages from extreme heat. The emerging economics literature on residential adaptation to date has primarily focused on high income countries (Barreca et al., 2016; Park et al., 2020; Heutel, Miller and Molitor, 2021). In conducting this study in a high loss, low income setting – which is not uncommon in many developing countries – we are able to provide causal evidence on the interaction between electricity infrastructure upgrades and adaptation to extreme heat. This is an important direction of research given that utilities often struggle with both cost recovery and reliable electricity service provision in low and lower-middle income countries – which are the same settings that are at the highest risk for future damages from extreme temperatures.

The paper proceeds as follows. Section 2 provides background information on Pakistan's climate and electricity sector. Section 3 presents a simple model of the relationship between temperature and electricity consumption and losses, and how the infrastructure upgrade that makes electricity theft more costly interacts with temperature. Section 4 details the data employed in the analyses, which include electricity utility data as well as

gridded weather data. Section 5 describes the empirical models underpinning our estimations. Section 6 presents results and then Section 7 concludes.

2 Background

Karachi, Pakistan's largest city is exposed to frequent and intense heat waves, exacerbated by climate change and rapid urbanization. Karachi's average recorded temperatures have increased by 2.25 degrees Celsius over the last 60 years (Ilyas, 2024*a*). There has also been a substantial increase in its built-up area due to expansion of formal and informal settlements (Li et al., 2023). Rising temperatures coupled with urbanization create the urban heat island effect, whereby heat gets trapped in urban areas due to reduced green spaces, heat-absorbing construction materials, and emissions from human activities (Amin, 2024). Periods of extreme heat significantly impact residents' health and strain the city's power, water and health services infrastructure (Ilyas, 2024*b*).

Access to electricity for cooling is one of the ways residents can mitigate the adverse effects of heat. However, access to affordable and reliable electricity remains a persistent challenge in Karachi as well as in the rest of Pakistan. Electricity generation from the grid is primarily dependent on imported fossil fuels, and bulk of the installed capacity was contracted under expensive long-term take-or-pay contracts (Bacon, 2019). Historically, electricity retail tariffs for households were set below production costs, preventing distribution companies from fully recovering costs. Widespread informal electricity use and poor bill recovery also undermined utility cost recovery. These structural problems lead to chronic loadshedding, overburdened infrastructure, financial losses, and accumulation of receivables throughout the supply chain (Younas and Ali, 2021).[3]

Electricity in Karachi is provided by Karachi Electric (KE), a vertically integrated private utility. KE owns in-house generation capacity; however, it purchases more than half

[3]Ongoing reforms aim to eliminate electricity tariff subsidies and instead target support to low income households via the national social protection program (Profit, 2024).

of its electricity from the national grid. Its distribution tariffs are regulated and it faces significant financial losses due to informal usage and low bill payment rates. Unauthorized electricity connections, known as kundas, are widespread in Karachi. Kundas are typically attached to low-tension service cables near the point of use. Although KE actively monitors and removes kundas, their bare wire infrastructure allows quick reconnections. In many areas, residents secretly install kundas at night - especially during hot seasons when cooling needs increase - and remove them in the morning to avoid detection (Ahmad et al., 2024).

To combat electricity theft, KE introduced aerial bundled cables (ABCs) starting in 2015. These cables have a tightly bound design that prevents illegal tapping. After initial pilot testing, KE expanded ABC installations in 2018 to high-loss areas. The ABCs aimed mainly to reduce electrical theft, not improve the resilience of the system to normal weather damage or extreme weather events, nor reduce technical losses (Ahmad et al., 2024). The spatial and temporal variation in ABC installation creates a natural experimental setting in which to study formal and informal household electricity usage during hot temperatures.

3 Conceptual Framework and Hypotheses

We motivate our research hyptheses through a simple model of a household's choice to engage in theft, or procure electricity formally. While mathematical derivations are relagated to supplemental appendix A, we provide a sketch of the model and its testable hypothesis here.

For an agent, let $u(e,t)$ be their utility when they consume e units of electricity and the temperature is t degrees. Further assume that $u_e \geq 0$ and $u_t \leq 0$, i.e. electricity is a good, while higher temperatures lower utility.[4] The latter is appropriate for our setting

[4] A minor note on notation, for a differentiable function, say $f(x,y)$, we use f_x to denote the partial derivative of f with respect to x.

as Karachi is in a semi-arid tropical region and electricity is heavily used for the purposes of cooling.

Given t, the agent must decide whether to consume electricity formally, at cost $c(e)$, or pay some fixed kunda fee, K, to steal electricity. We assume that c is increasing, convex and differentiable, and that kunda use is not costless ($K > 0$).[5] Analyzing the agent's choice to use a kunda, we get the following result, our model yields the following set of testable hypotheses.

First, and perhaps intuitively, our model suggests that as temperatures rise, both electricity consumption and losses should rise.

Hypothesis 1. *As temperatures rise, electricity consumption increases.*

Hypothesis 2. *As temperatures rise, utility losses also increase.*

Second, given the assumption that ABC wiring makes illegal connections more expensive, our model predicts a reduction in theft.

Hypothesis 3. *At a given temperature, ABC wiring reduces the level of losses in a feeder-line.*

Finally, and the main focus of our analysis, is the relationship between temperature and ABC wiring. Our model predicts that as temperatures rise, losses in ABC areas also rise, reducing the ABC effect.

Hypothesis 4. *As temperatures rise, the ability of ABCs to mitigate losses, falls.*

4 Data

The analyses utilize data from multiple sources. First, through a non-disclosure agreement, the utility shared extensive data at the feeder-line, transformer, and consumer lev-

[5] KE's use of pricing slabs imposes convexity, though we note that the actual cost function has discontinuities at each slab's cutoff. The cost of kunda captures both the expected fine at detection, and the fact that focus groups indicate there are informal groups that charge monthly fees to facilitate kunda use.

els. In addition, we collected survey data for a sample of utility customers, and utilized publicly available data on weather and temperature

4.1 Utility Feeder-Line Outcomes and Cable Conversion

We assembled a comprehensive and unique dataset including estimates of feeder-level losses, percentage of billed amount paid, utility claims, consumer complaints, consumer numbers and date of cable conversions of transformers from KE.[6] Further details of the utility datasets are as follows:

Utility Financial Indicators. There are two variables that are primary indicators of utility financial health: *losses* and *revenue recovery*, respectively. The data on feeder-level monthly losses and revenue recovery cover all feeder-lines in Karachi from January 2018 to October 2020. Losses are measured as the difference between units sent out and units billed and then divided by units sent out. Losses are therefore the proportion of the electricity sent out that is not billed. Note that this is in essence an estimate of total T&D losses, as there is no way to distinguish between unbilled consumption and technical losses. Revenue recovery is defined as the ratio of net credit to billing. In other words, it is proportion of billed electricity consumption that is actually paid.

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

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

4.2 Household Survey and Electricity Bills

In October and November 2021, we surveyed approximately 3,000 residential customers across 150 transformers. More details on survey design and implementation can be found in Ahmad et al. (2024). The questionnaire collects information on basic household characteristics, demographics, and other outcomes related to electricity consumption, e.g., appliance ownership and usage, as well as household expenditures. Among the surveyed households, almost all of them report having fans but only 3% report having air conditioners (See Figure 1).

For this set of surveyed households, we obtain the corresponding customer-level billing records from KE. The sample covers the period between June 2018 and August 2021. In the data, we observe information on monthly billed units of electricity (both the kWh and the monetary amount), the amount and date of bill payment, total monetary amount due to KE, and the billing category mode (BCM).

4.3 Weather

We assemble weather information from the ERA5-Land reanalysis data provided by the European Center for Medium-Range Weather Forecasts (ECMWF). Reanalysis data are generated by combining atmospheric models with local observations. ERA5-Land provides global daily surface weather records on a $0.1^\circ \times 0.1^\circ$ grid (approximately 9×9 km) starting from 1950. We identify the grids in Karachi, Pakistan and retrieve a series of weather variables, including temperature, precipitation, wind speed and direction, etc.

To combine the electricity and weather data, we match pole mounted transformers (PMTs) to weather records at the closest ERA5-Land grid node. For the feeder-line-level analysis, we aggregate the PMT-level weather data to the feeder-line-level by taking the average over all PMTs within a feeder line. For the customer-level analysis, we match customers to weather records at the PMT that they belong to. After constructing the daily

weather data for PMTs and feeder lines, we aggregate the data to monthly level by either taking the average or summing the number of days over each billing month. Figure 2 plots the distribution of daily temperature by calendar month in Karachi. During hot months such as April to November, almost all the days have daily average temperatures above 24°C and the average daily maximum temperature can reach 35°C.

5 Empirical Strategy

We begin by estimating the relationship between temperature and electricity outcomes. Our empirical model leverages random variation in realized temperature for a given area and over time.

For feeder line (or customer) i in billing month t, we estimate the following model:

$$y_{it} = \sum_{b \in B \setminus \{<21\}} \beta_b T_{bit} + \gamma \mathbf{X}_{it} + \alpha_i + \delta_{y(t)} + \phi_{q(t)} + \varepsilon_{it}, \tag{1}$$

where y_{it} is either the feeder-line-level electricity outcomes (including units sent out, billed and unbilled units, customer complaints, and infrastructure damage) or customer-level billed consumption. T_{bit} are binned measures of daily average temperature. We use this binned approach to capture potentially important nonlinearity in the electricity-temperature relationship (Auffhammer, 2022). Specifically, we sort daily average temperature (°C) into five bins $B = \{< 21, 21-24, 24-27, 27-30, > 30\}$. Then, for each i and billing month t, we count the number of days that daily average temperature falls into each bin $b \in B$ and denote this as T_{bit}. For the regression, since the number of days in a billing month is fixed, we omit one category (<21°C) and therefore β_b captures the change in electricity outcomes associated with having one additional day that daily average temperature falls into bin b in a billing month, relative to a day in the <21°C bin.

$\mathbf{X}_{it}$ is a vector of other weather conditions, including total precipitation and average

wind speed in a billing month. We control for these variables using a second-order polynomial in all regressions to account for the nonlinearity in people's behavior change on rainy or windy days in ways that might also affect electricity consumption.

We include a set of fixed effects to control for unobservable confounding factors. α_i are feeder-line (or customer) fixed effects that account for time-invariant differences across feeder lines (or customers) that might be tied to electricity outcomes. We have year fixed effects $\delta_{y(t)}$ and quarter-of-year fixed effects $\phi_{q(t)}$ to capture common trends and seasonality. Standard errors are clustered at the IBC level to account for serial correlation within IBC regions.

To examine how cable upgrades affect electricity outcomes under different temperature conditions, we estimate the following interaction model.

$$y_{it} = \sum_{b \in B \setminus \{<21\}} \beta_b T_{bit} + \sum_{b \in B} \eta_b T_{bit} \times \text{ABC}_{it} + \gamma \mathbf{X}_{it} + \alpha_i + \delta_{y(t)} + \phi_{q(t)} + \varepsilon_{it}. \tag{2}$$

Compared to Equation 1, the above equation adds interactions between temperature bins (T_{bit}) and the indicator for cable upgrades (ABC_{it}). For the feeder-line-level analysis, ABC_{it} equals 1 if a feeder line i already has at least one transformer with theft-resistant cables installed in month t. For the customer-level analysis, ABC_{it} equals 1 if the transformer that serves customer i already has theft-resistant cables installed in month t.

In this equation, β_b characterizes the relationship between temperature and electricity outcomes for the baseline scenario without cable upgrades. These coefficients are estimated relative to the omitted $<21°\text{C}$ bin. η_b captures how cable upgrades change electricity outcomes for each temperature bin, relative to the baseline scenario without cable upgrades.[7] To interpret the results for a specific temperature bin b, the total effect under the cable upgrade scenario is $\beta_b + \eta_b$. This combined effect characterizes the elec-

[7] Unlike β_b, η_b is identified for all temperature bins, including the $<21°\text{C}$ bin, because the timing of theft-resistance cable installation differs across transformers. Therefore, η_b for $<21°\text{C}$ measures the change in electricity outcomes for a day with cable upgrades relative to a day without cable upgrades when the daily average temperature is below 21°C.

tricity outcomes under different temperature conditions when theft-resistant cables have been installed, relative to the omitted <21°C bin without cable upgrades.

6 Results

6.1 Heat and Feeder-Line Electricity Outcomes

We start by estimating Equation 1 to examine the relationship between temperature and various electricity outcomes at the feeder-line level. A key advantage of our feeder-line-level data is its ability to capture unbilled electricity consumption, which we measure as the difference between total electricity sent out and billed units. This unbilled component is often overlooked in prior studies relying solely on electricity bill data.

Figure 3 presents the coefficient estimates along with their 95% confidence intervals for total electricity sent out, billed units, and unbilled units, measured in natural logarithms. Consistent with hypotheses 1 and 2, across all three panels, we observe consistent evidence that electricity consumption, both billed and unbilled, increases significantly as temperature rises. The left-most panel illustrates the change in total electricity sent out as temperatures rise. To interpret the graph, note that the coefficient on >30°C temperature bin implies that one additional day over 30°C increases total electricity consumption by almost 3%, relative to a day with temperatures below 21°C. In the middle and right panel, we decompose the total electricity consumption into billed and unbilled units, respectively. Both components show substantial increases in response to high temperatures. Notably, unbilled electricity consumption is more responsive to temperature changes than billed consumption, exhibiting a much sharper increase during hot days. Specifically, with one additional day above 30°C, billed electricity consumption increases by roughly 2% while unbilled electricity consumption rises by about 5%.

These findings suggest that during periods of hotter temperatures, poorer households may rely more on informal or unauthorized channels, such as electricity theft, to

meet their rising cooling demand and avoid higher electricity bills. While this unbilled electricity consumption helps vulnerable households mitigate the risks associated with extreme heat, it also undermines the financial sustainability of electric utility companies by straining their revenue recovery efforts. This dual impact highlights the challenges utilities face in balancing equitable energy access with financial stability. Our results provide novel evidence on how unbilled electricity consumption responds to temperature, complementing prior literature that documents a relatively flat relationship between billed electricity consumption and temperature in low-and-middle-income countries (Rode et al., 2021).

To understand the motivations and potential channels for unbilled electricity consumption, we explore how temperature affects other consumer behaviors, such as complaints about electricity bills and reports of infrastructure damage. Given the count nature of these variables, we estimate Equation 1 using Poisson pseudo-likelihood regressions. Figure 4 plots the coefficient estimates. The top panel shows the impact on customer bill complaints. We find that during hotter months, when electricity bills tend to be high, there are much more customer complaints about their bills. The middle and bottom panels show the impact of temperature on the number of claims filed by the utility company regarding intentional infrastructure damage. The results suggest that the number of reported damage increases during hot temperature days. These findings reveal the different ways that customers may tamper the electricity distribution system and avoid high electricity bills especially in hot temperatures.

6.2 Heat and Billed Electricity Consumption of Formal Customers

Building on the feeder-line-level analysis of both billed and unbilled electricity consumption, we now shift to a more granular investigation of customer-level billed consumption among surveyed households, all of whom are formal customers. This analysis allows us to better understand the intensive margin of household electricity consumption through

formal channels and their heterogeneous responses based on appliance ownership and usage patterns.

Figure 5 presents the coefficient estimates and their 95% confidence intervals for the relationship between temperature and customer-level billed electricity consumption, measured in natural logarithms. The left panel shows the impact on billed electricity units (in kWh), while the right panel illustrates the impact on billed amounts (in PKR). The results indicate that both billed electricity units and amounts increase significantly with higher temperatures. For days with temperatures above 30°C, billed electricity units rise by approximately 2%, and billed amounts increase by around 3%, relative to days with temperatures below 21°C. These findings confirm the heightened electricity demand and the resulting increase in electricity bills for formal customers during periods of extreme heat, likely driven by increased usage of cooling appliances.

Next, we analyze the heterogeneity in billed electricity consumption by appliance ownership and usage patterns. Figure 6 presents the heterogeneous effects of temperature on billed units across households with different cooling appliance usage. In the left panel, households are divided into two groups based on whether their self-reported daily fan usage is above or below the median (i.e., 8 hours per day). The right panel categorizes households into three groups: those without air conditioners, those with air conditioners used for $\leq$3 hours per day, and those with air conditioners used for $>$3 hours per day.

The results indicate slight differences in electricity consumption responses to temperature across these groups. In the left panel, households with fan usage exceeding 8 hours per day exhibit increases in billed electricity units comparable to those with lower fan usage as temperatures rise. In contrast, the right panel highlights that households with air conditioner – particularly those using them more – experience the largest increases in billed electricity consumption on extremely hot days. These findings confirm the role of cooling appliances in driving electricity consumption during high temperatures.

6.3 Cable Upgrades and Electricity-Temperature Relationship

6.3.1 Cable Upgrades, Heat, and Feeder-Line Electricity Outcomes

To address high electricity losses, KE initiated a cable upgrade program, replacing traditional wires with aerial bundled cables (ABCs), which significantly raised the cost of informal electricity consumption through illegal connections. Following these upgrades, there was a significant reduction in electricity losses and an improvement in the utility company's revenue recovery (Ahmad et al., 2024).[8] While these infrastructure upgrades benefit the utility company, they may also limit households' ability to mitigate heat-related risks by restricting their consumption of electricity-intensive cooling services. To evaluate how these infrastructure investments influence the electricity-temperature relationship, we estimate Equation 2 to analyze changes in electricity consumption across different temperature conditions following the cable upgrades.

Figure 7 illustrates the estimated changes in feeder-line-level electricity consumption in response to temperature and cable upgrades. The gray dots represent electricity consumption across different temperature ranges without cable upgrades, while the blue dots depict electricity consumption under the corresponding temperature conditions but with cable upgrades.[9] The reference group is comprised of days with daily average temperature below 21°C and without cable upgrades, with the corresponding coefficient scaled to zero.

The top panel shows the impacts on electricity sent out. Across all temperature ranges, cable upgrades reduce total electricity consumption, which is consistent with the findings in Ahmad et al. (2024). The reduction in total electricity consumption is particularly pronounced in days with moderate temperature (i.e., <27°C). However, during hotter days when daily average temperature exceeds 27°C, the decline in electricity con-

[8] In Appendix Figure B1, we replicate the results in Ahmad et al. (2024) but instead using the logarithm of total unbilled electricity units as the outcome variable.

[9] The gray dots plot β_b and the blue dots plot $\beta_b + \eta_b$ both estimated from Equation 2.

sumption following cable upgrades becomes more subtle and is not statistically significantly different from consumption levels without cable upgrades. This pattern suggests that while cable upgrades effectively reduce electricity usage under moderate conditions, their impact may diminish during periods of high demand driven by essential cooling needs.

Next, the middle and bottom panel of Figure 7 present the impacts on billed and unbilled electricity consumption, respectively. Consistent with the pattern observed for total electricity sent out, we find that cable upgrades significantly reduce unbilled electricity consumption across all temperature ranges, with the reduction being more pronounced on days with moderate temperatures (i.e., below 27°C). This suggests that cable upgrades effectively limit unauthorized electricity usage, particularly under moderate temperature conditions where discretionary or informal consumption may be more elastic.

In contrast to unbilled units, the middle panel shows no significant change in billed electricity consumption following the cable upgrades. These findings suggest that customers who previously relied on informal and unauthorized channels substantially reduce their overall electricity consumption, particularly during moderate temperature days. This may suggest that higher costs and barriers to illegal connections introduced by cable upgrades result in a net reduction in electricity usage, particularly among poorer households that may not have been previously formally connected.

Consistent with hypothesis 4, during hotter days (above 27°C), the reduction in unbilled electricity consumption diminishes, indicating that at higher temperatures, most customer's threshold for informal usage is crossed and that customers may resort to alternative informal methods, such as meter tampering, to meet their persistent electricity needs for powering essential cooling appliances. This is partly confirmed by Figure 8, which shows the impacts of temperature and cable upgrades on customer bill complaints and infrastructure damage. Following cable upgrades, there is a general increase in bill complaints, indicating heightened dissatisfaction or financial strain among customers. In-

terestingly, while cable upgrades lead to a reduction in reported intentional wire damage, there is a slight increase in reported incidents of meter damage, suggesting a possible shift in the methods customers use to bypass formal electricity channels.

6.3.2 Cable Upgrades, Heat, and Billed Consumption of Formal Customers

To understand how formally contracted customers' electricity consumption responds to temperature and cable upgrades, we estimate Equation 2 using the customer-level data for our surveyed households. Figure 9 presents the estimated billed electricity units (left panel) and monetary amounts (right panel) under various temperature ranges with and without cable upgrades. For these formal customers, we find that, following cable upgrades, their billed electricity consumption – measured both in units and monetary amounts – decreases in moderate temperatures ($<24^{\circ}$C) but increase in hot temperatures ($>24^{\circ}$C). The increase in electricity bills during hot temperature days likely reflects improved billing accuracy by the utility company following the cable upgrades, as previously available illegal connection channels are largely blocked. The reduction in billed consumption during moderate temperature days likely reflects a form of "comfort-smoothing" behavior. Specifically, these customers may reduce discretionary electricity usage on moderate temperature days to save on costs, allowing them to accommodate potentially higher electricity bills during hot days, when informal consumption channels are less accessible, and their persistent demand for essential cooling services is now accurately billed.

Figure 10 illustrates the heterogeneous responses of billed electricity units to temperature and cable upgrades, across rich versus poor households. Households are classified into two groups based on whether their self-reported total expenditure falls above or below the 95th percentile of the sample. We then estimate Equation 2 separately for each group. The results suggest that our previously documented "comfort-smoothing" behavior mainly is primarily observed among relatively poorer households. For richer

households, while their electricity bills increase on hot days (>24°C) following cable upgrades, their billed consumption during moderate temperature days remains unchanged. This indicates that wealthier households are less likely to adjust their discretionary electricity usage during moderate temperature days, likely due to a greater ability to afford the higher electricity bills.

7 Conclusions

In this paper we examine how poor households in Karachi, Pakistan adapt to extreme heat in the context of electricity consumption and infrastructure improvements aimed at reducing electricity theft. We find that both billed and unbilled electricity consumption increase significantly with rising temperatures. However, unbilled consumption (indicative of theft) is more responsive, particularly on extremely hot days. The installation of theft-resistant aerial bundled cables (ABCs) significantly reduced unbilled electricity consumption, especially on moderate temperature days. However, this reduction was less effective during extreme heat, indicating that households may find alternative ways to bypass the system when cooling needs become urgent. For formal utility customers, post ABC installation, we also observe "comfort smoothing" behavior which suggests that households cut back on moderate-temperature electricity use to manage higher bills during extreme heat. This behavior is more pronounced for lower income households.

These results highlight the need for suitable policies to balance the goals of utility cost recovery with equitable access to electricity for climate adaptation. While lifeline tariffs offer a conventional policy option to protect low-income consumers, they need to be appropriately designed to target truly vulnerable households. Other policy options can include subsidization of energy efficiency cooling solutions and provision of renewable energy options such as individual or community based solar systems. Such systems would reduce dependence on the main grid and provide an additional coping mechanism

during periods of extreme heat. Future research is needed to determine the viability and impact of such policies.

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Figures and Tables

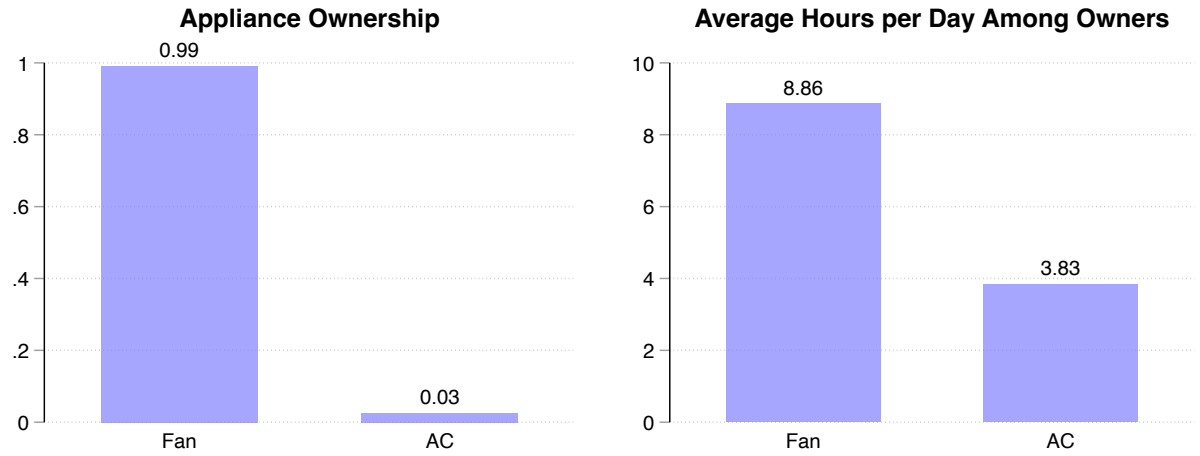


Figure 1: Self-Reported Cooling Appliance Ownership and Usage

Notes: This figure displays household self-reported ownership and usage patterns of fans and air conditioners. The data comes from our household survey conducted in Fall 2021. The left panel shows the share of households reporting to have these cooling appliances. The right panel shows the average usage hours in a typical day reported by households who claimed owning these appliances.

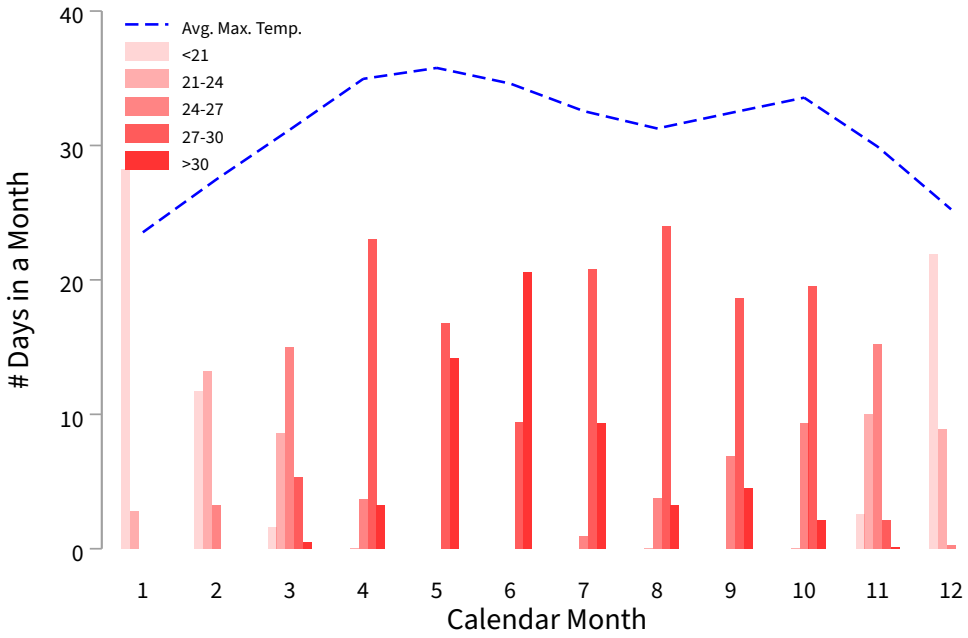


Figure 2: Distribution of Daily Temperature by Month

Notes: This figure displays the distribution of daily temperature (°C) in Karachi by calendar month. The red bars represent the average number of days per calendar month, over the 2018-2021 sample period, with daily average temperature falling within specific ranges. The dashed blue line illustrates the average maximum temperature for each calendar month.

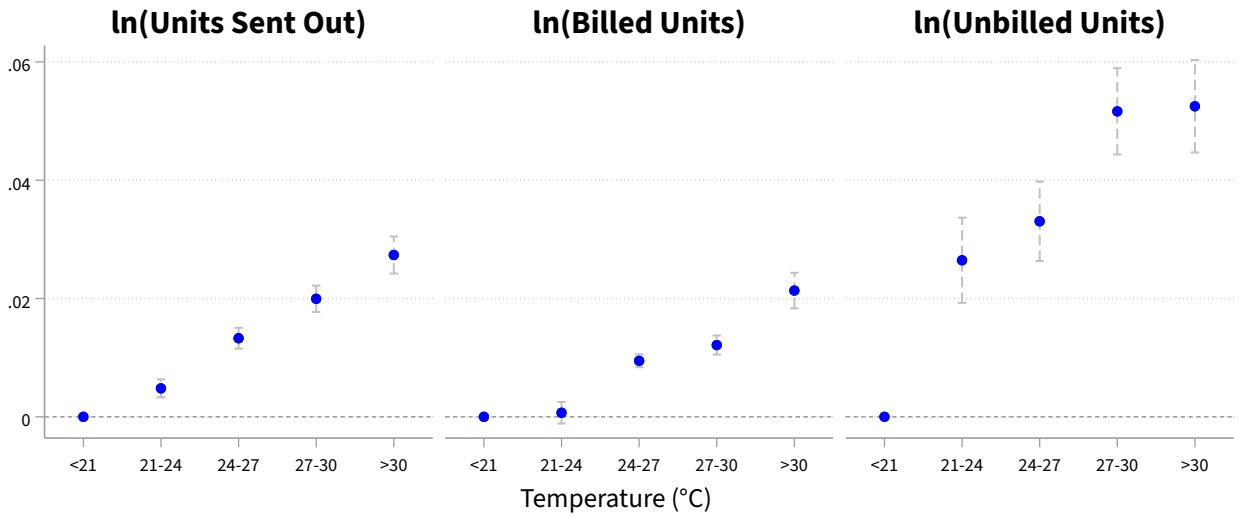


Figure 3: Heat and Electricity Consumption at the Feeder-Line Level

Notes: This figure displays the estimated effect of temperature on electricity outcomes, including total electricity sent out, billed units, and unbilled units, using the feeder-line-level data. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. The omitted temperature category (<21°C) serves as the reference group for comparison. Blue dots are coefficient estimates. Gray brackets are 95% confidence intervals centered on the estimated coefficient.

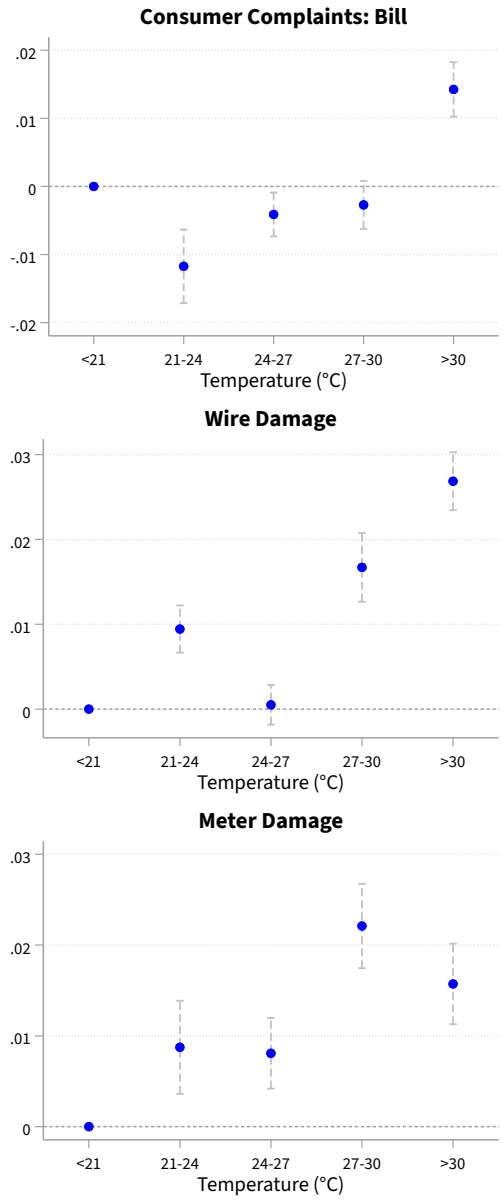


Figure 4: Heat, Consumer Complaints, and Infrastructure Damage

Notes: This figure displays the estimated effect of temperature on the number of customer bill complaints and utility company's claims on infrastructure damage, using the feeder-line-level data. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. The omitted temperature category (<21°C) serves as the reference group for comparison. Blue dots are coefficient estimates from Poisson pseudo-likelihood regressions. Gray brackets are 95% confidence intervals centered on the estimated coefficient.

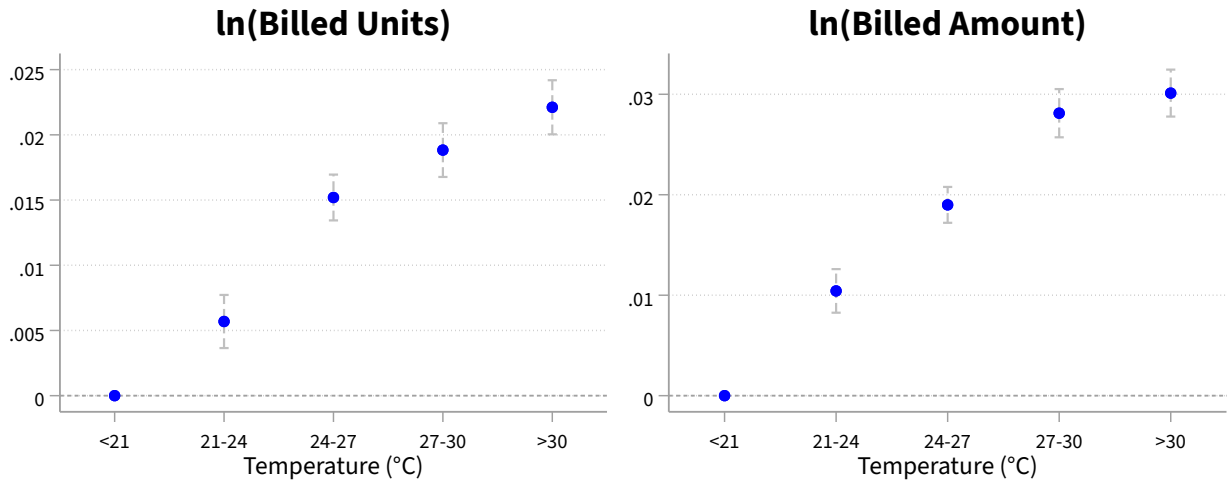


Figure 5: Heat and Billed Electricity Consumption of Formal Customers

Notes: This figure displays the estimated effect of temperature on billed electricity consumption (i.e., units and amount) of formal customers using the customer-level data. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. The omitted temperature category (<21°C) serves as the reference group for comparison. Blue dots are coefficient estimates. Gray brackets are 95% confidence intervals centered on the estimated coefficient.

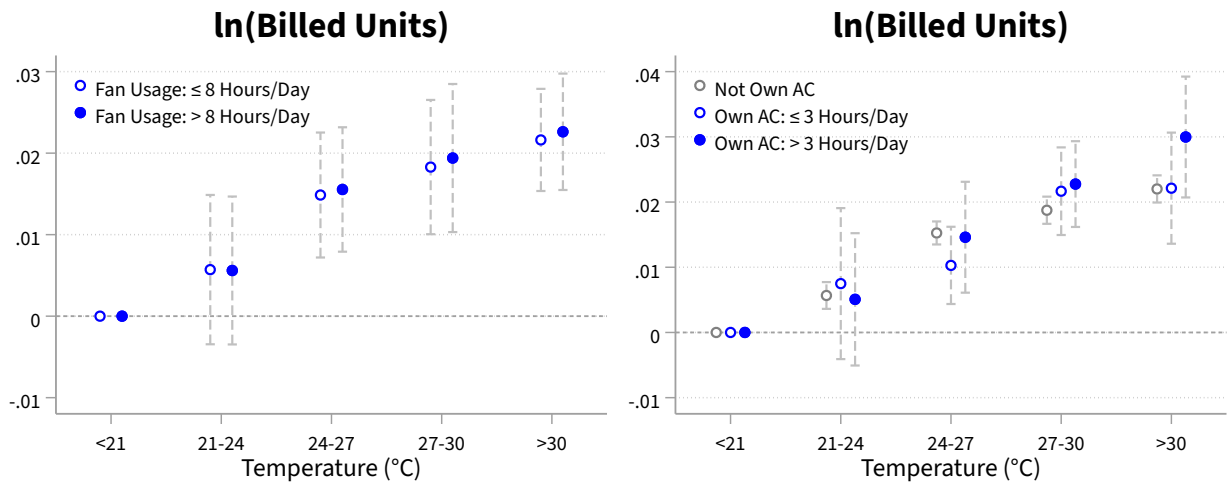


Figure 6: Heat and Customer-Level Billed Electricity Consumption by Appliance Usage

Notes: This figure displays the estimated heterogeneous effects of temperature on billed electricity units of formal customers using the customer-level data. In the left panel, we classify households into two groups, based on whether their self-reported daily hours of fan usage is above or below the median (i.e., 8 hours/day). In the right panel, we classify households into three groups based on whether they reported to have air conditioners and if so whether the daily hours of usage is above or below the median (i.e., 3 hours/day). The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. The omitted temperature category (<21°C) serves as the reference group for comparison. Blue dots are coefficient estimates. Gray brackets are 95% confidence intervals centered on the estimated coefficient.

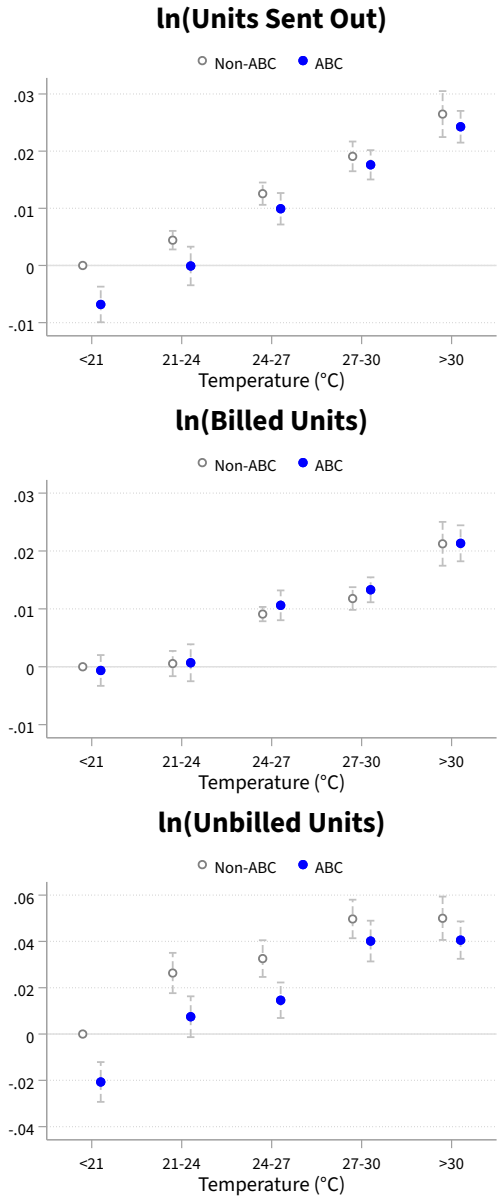


Figure 7: Heat, Theft-Resistance Cables, and Feeder-Line Electricity Consumption

Notes: This figure displays the estimated effect of temperature and cable upgrades on electricity outcomes, including total electricity sent out, billed units, and unbilled units, using the feeder-line-level data. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. Gray dots depict the estimated effect of temperature without cable upgrades. Blue dots depict the estimated effect of temperature with cable upgrades. Gray brackets are 95% confidence intervals. The omitted category, i.e., daily average temperature below 21°C without cable upgrades, serves as the reference group for comparison.

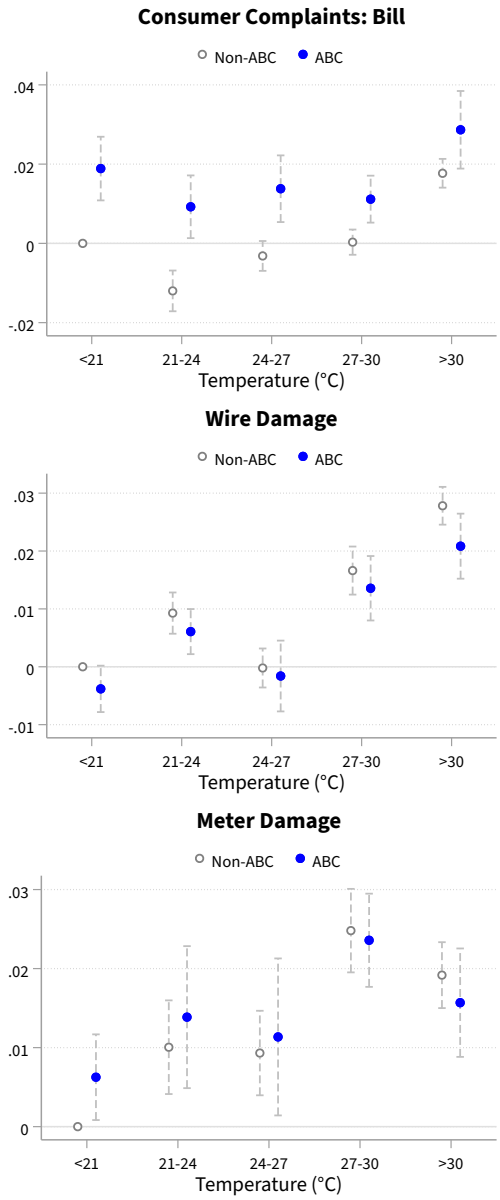


Figure 8: Heat, Theft-Resistance Cables, Complaints and Infrastructure Damage

Notes: This figure displays the estimated effect of temperature and cable upgrades on the number of customer bill complaints and utility company's claims on infrastructure damage, using the feeder-line-level data. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. Coefficients are from Poisson pseudo-likelihood regressions. Gray dots depict the estimated effect of temperature without cable upgrades. Blue dots depict the estimated effect of temperature with cable upgrades. Gray brackets are 95% confidence intervals. The omitted category, i.e., daily average temperature below 21°C without cable upgrades, serves as the reference group for comparison.

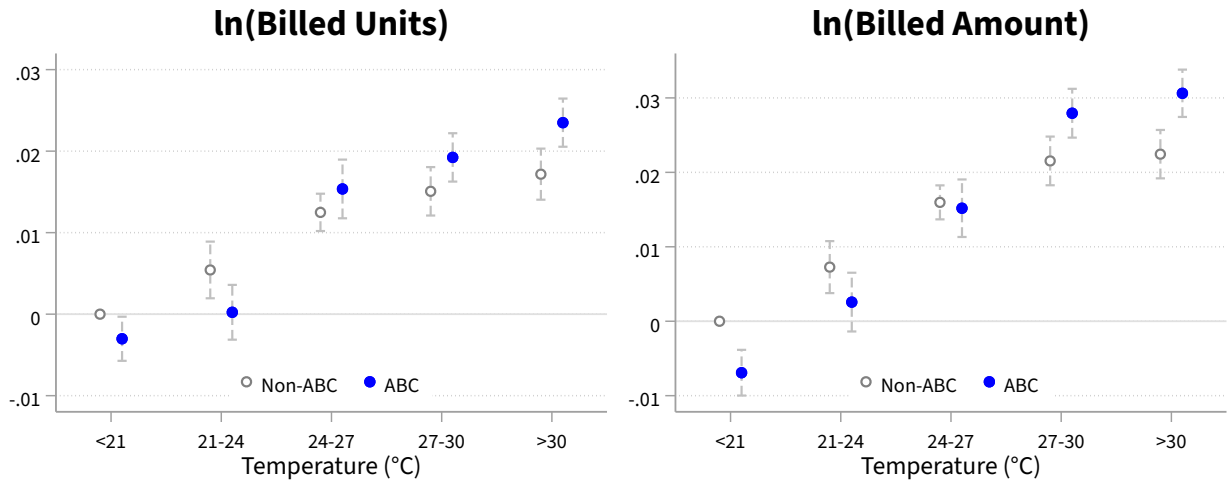


Figure 9: Heat, Theft-Resistance Cables, and Billed Consumption of Formal Customers

Notes: This figure displays the estimated effect of temperature and cable upgrades on on billed electricity consumption (i.e., units and amount) of formal customers using the customer-level data. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. Gray dots depict the estimated effect of temperature without cable upgrades. Blue dots depict the estimated effect of temperature with cable upgrades. Gray brackets are 95% confidence intervals. The omitted category, i.e., daily average temperature below 21°C without cable upgrades, serves as the reference group for comparison.

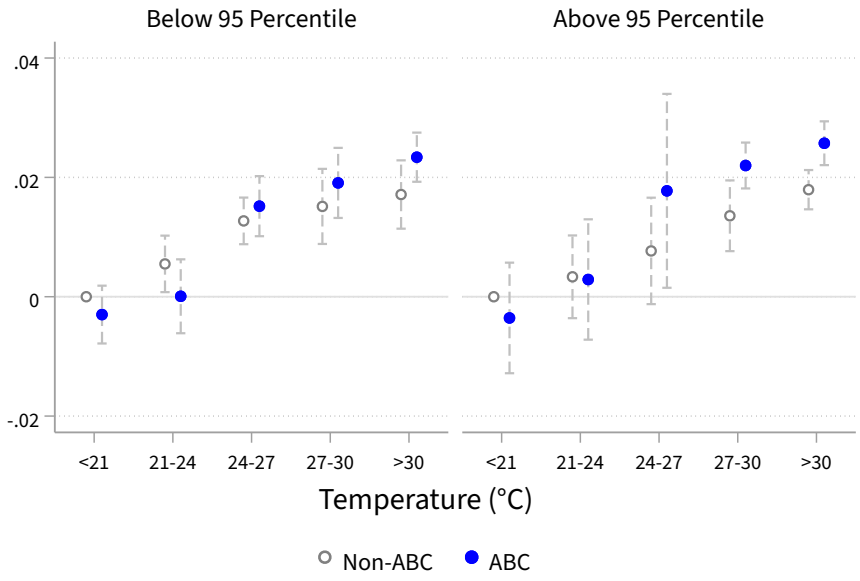


Figure 10: Heat, Theft-Resistance Cables, and Billed Units – Poor vs Rich

Notes: This figure displays the estimated effect of temperature and cable upgrades on on billed electricity units of formal customers using the customer-level data. We classify households into two groups, based on whether their self-reported total expenditures are below (shown in the left panel) or above (shown in the right panel) the 95 percentile of our sample, and estimate the models separately for each group. The horizontal axis represents the number of days in a billing month with daily average temperature falling into specific ranges. Gray dots depict the estimated effect of temperature without cable upgrades. Blue dots depict the estimated effect of temperature with cable upgrades. Gray brackets are 95% confidence intervals. The omitted category, i.e., daily average temperature below 21°C without cable upgrades, serves as the reference group for comparison.

Online Appendix

Constrained Cooling: Electricity Infrastructure, Heat, and Household Responses in Pakistan

Husnain F. Ahmad Ayesha Ali Robyn C. Meeks
Zhenxuan Wang Javed Younas

A Conceptual Framework: Mathematical Derivations **SI-1**

B Additional Figures and Tables **SI-5**

A Conceptual Framework: Mathematical Derivations

In this appendix section, we present detailed derivations of our conceptual framework. For ease of readability, we begin derivations from the begining, yielding a self contained section.

We motivate our analysis with an individual level model of electricity consumption and the choice to use formal or informal electricity. For an agent, let $u(e,t)$ be their utility when the consume e units of electricity and the temperature is t degrees. Further assume that $u_e \geq 0$ and $u_t \leq 0$, i.e. electricity is a good, while higher temperatures lower utility.[10] The latter is appropriate for our setting as Karachi is in a semi-arid tropical region and electricity is heavily used for the purposes of cooling.

Further we assume that utility is concave in electricity use ($u_{ee} \leq 0$) and that the marginal utility of electricity is higher at higher temperatures, i.e. $u_{et} \geq 0$. The latter is assumed, as in a semi-arid tropical climate the marginal benefit of cooling should increase as temperatures rise. Alternatively, we can also view this assumption from the perceptive of the marginal damage heat causes. Our assumption formalizes that higher electricity consumption can better mitigate the damage caused by rising temperatures.

Now consider first an agent who can only consume electricity formally, through the grids, with cost $c(e)$. Given the slab structure of pricing deployed by KE, we assume that c is increasing, convex and for ease of analysis continuously differentiable.[11] Then, our consumer's objective function, given temperature t is

$$\max_{e \in [0,\bar{e}]} \{u(e,t) - c(e)\},$$

where $\bar{e}$ is the maximum amount of electricity the consumer can use, and may be a function of how many appliances the individual has at their disposal.[12] Then at an interior solution, the optimal level of consumption $e^f(t)$ is implicitly defined by the equation

$$u_e(e^f, t) = c_e(e^f). \tag{A1}$$

[10] A minor note on notation, for a differentiable function, say $f(x,y)$, we use f_x to denote the partial derivative of f with respect to x.

[11] We note that while the "slabs" used by KE do induce convexity, the actual cost function has discontinuities at each tier's cutoff.

[12] For simplicity, we avoid incorporating a budget constraint. The model can be extended, such that utility is also a function of non-electricity consumption, say $U(e, I - c(e), t)$, where I is the budget constraint. Such a model would increase notational complexity, but not meaningfully change our results. The current model is in fact identical to one where utility is quasi-linear in non-electricity consumption, such that the agent's utility is $U(e,x,t) = u(e,t) + x$, where x is non-electricity consumption and the budget constraint is $c(e) + x \leq I$.

In line with our intuition, electricity consumption is then increasing in temperature, as when t increases, u_e increases as well (recall that $u_{et} \geq 0$).[13]

Now let us introduce informal usage, in our context through the use of kundas. Kundas allow individual's to bypass the meter and any form of billing. They are the predominant form of electricity pilferage when there are bare wires, importantly for our context they are not costless. First, kundas (and other meter tampering methods) are physically detectable, and one can be caught for using kundas, and fined. Second, from focus group discussions in the area, there are groups that "facilitate" kunda usage and charge some fixed monthly fee for the service. We incorporate both the expected cost of detection and the fixed fee model directly as the fixed cost of a kunda connection, K. Then for a kunda user, the net utility from consuming e units of electricity, when the temperature is t is simply $u(e,t) - K$, and given there is no marginal cost of consumption, it is obvious that if a kunda is used, the agent would consume at their capacity constraint $\bar{e}$.

Putting these two together, an individual with the option to use a kunda, would use a kunda when $u(\bar{e},t) - K \geq u(e^f,t) - c(e^f)$. Note that it may seem that we are assuming that the user is either formal or informal. Our focus groups highlight how households may use both channels, whereby they report using kunda's for higher loads and/or when risk of detection is low, e.g. to run air conditioners at night. While our model does not incorporate this directly, we can account for it by the "level" of our decision to smaller time frames. So for example, our model may not consider a household itself, but the decision of the household to use a kunda for the next hour or not. Then in a day there could be times when they use a kunda, and times when they do not.

Then the above inequality defines a threshold temperature T, such that for all $t > T$, the consumer would use a kunda, otherwise they would use formal channels. To confirm that such a threshold exists and is unique, note that we can express the threshold using the following function

$$\tau(t) = u(\bar{e},t) - u(e^f,t) + c(e^f) - K,$$

such that the threshold T is implicitly defined by $\tau(T) = 0$. It is obvious then that τ is continuous given our assumptions, and we note that τ is increasing in t as derivating with respect to temperature yields $\tau_t = u_t(\bar{e},t) - u_t(e^f,t) \geq 0$, as $\bar{e} \geq e^f$ and $u_{et} \geq 0$.

Then let $t \in [\underline{t},\bar{t}]$ be the set of potential temperatures. Then for the interesting case where at some temperatures individual's steal and at others they don't, assume that for

[13] To see this more formally, we can use the implicit function theorem on equation (A1), which yields $e^f_t = \frac{u_{et}}{c_{ee} - ue\bar{e}} \geq 0$ by our assumptions.

all K, $\tau(\underline{t}) \leq 0$ and $\tau(\bar{t}) \geq 0$.[14] Then, for any K, by the intermediate value theorem a threshold $T \in [\underline{t}, \bar{t}]$ exists, and as τ is increasing in t, is unique.[15]

For understanding the effects of ABC wiring on electricity consumption, we note that ABCs made kunda's harder to use. In our model, this translates to higher costs of kunda useage (K), as in area's with ABC wiring, if individuals steal electricity, they may have to use more costly methods (e.g. direct meter tempering, drilling ABC wires, etc.).

So as a last step in the individual level model, we wish to determine the effect changes in K have on a consumer's choice to use a kunda. To do so, we note that τ is obviously decreasing in K, then increases in K would "shift" the graph of $\tau(t)$ downwards, increasing the threshold value T. Therefore if ABCs increase K, we can hypothesize that the threshold for kunda use for two individuals who are identical in all dimensions except that one is in an area with ABC wiring while the other is without, is such that the threshold with ABCs is higher than that without, i.e. $T^{ABC} \geq T^{\overline{ABC}}$.

We can now extend this result to utility losses, in particular how we expect losses to change as temperatures rise in both ABC and non-ABC areas. Consider then a feeder without ABCs first. In such a feeder, different consumers would have different preferences and constraints, and so assume that there is some distribution of threshold temperatures at this feeder, with c.d.f. $G_{\overline{ABC}}$ over $[\underline{t}, \bar{t}]$. Now if we were to convert this feeder to one with ABCs, by our result above ($T^{ABC} \geq T^{\overline{ABC}}$), the threshold for each individual would (weakly) increase, such that the distribution of values post ABC, G_{ABC}, would first order stochastically dominate $G_{\overline{ABC}}$.

Then at any particular temperature, losses for KE at feeder $i \in \{ABC, \overline{ABC}\}$ are directly proportional to the number of individuals using kundas, i.e. $G_i(t)$, which is increasing in t. Furthermore, the differences in losses, $\delta(t) = G_{ABC}(t) - G_{\overline{ABC}}(t)$ will also vary with temperature, and while the exact nature of the difference depends on the underlying distribution of individual characteristics, as temperatures get closer to $\bar{t}$, the differences in losses would get smaller and smaller.

To see this, consider a hypothetical feeder without ABCs, where the distribution of threshold values is given by a normal distribution over 40 and 80 degrees. Further assume that when the feeder is converted to ABC wiring, the threshold value for each individual rises by 20 degrees. As can be seen by the plot of these CDFs in Figure A1, as temperature rises, the differences in losses converges to zero.

We therefore expect that on days with higher temperatures, the differences in losses

[14] If these assumptions don't hold, and say for some K $\tau(\underline{t}) \geq 0$, then $T = \underline{t}$ for such a K. As we will show later, τ is also decreasing in K, then if for a K, $T = \underline{t}$, then it is also the threshold for all lower values of K's. So our directional results remain unchaged. The inverse is true for the other assumption.

[15] We note that both τ and T are in fact functions of K. We suppress this notation for simplicity.

among ABC and non-ABC feeders would diminish.

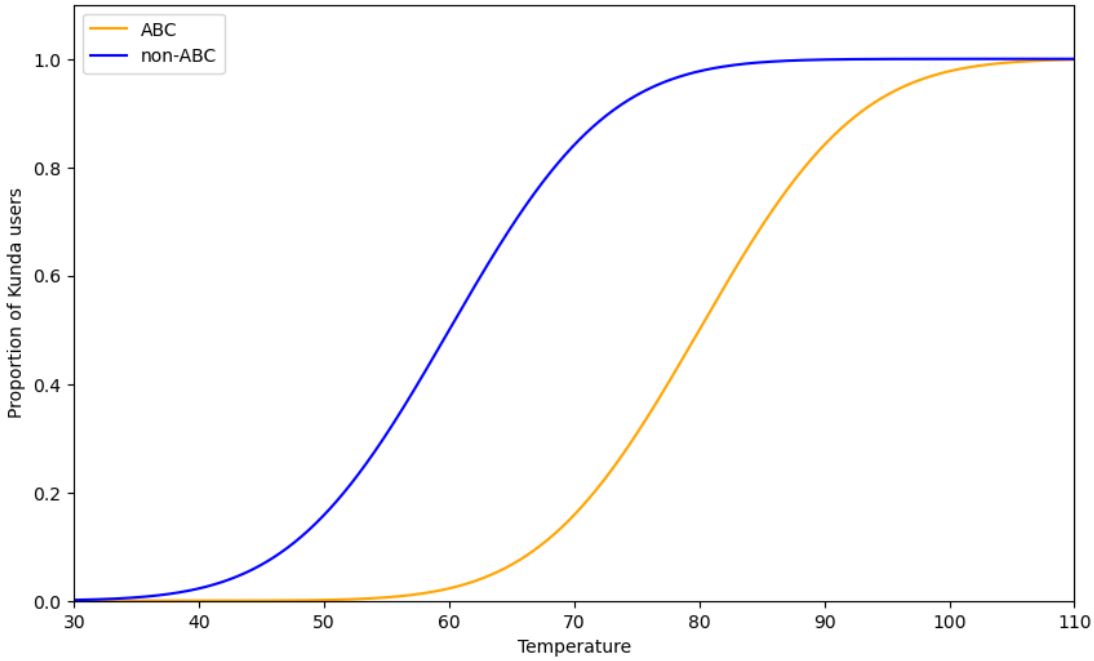


Figure A1: Illustration of shift in distribution of kunda useage with ABC installation

Notes: The figure plots the hypothetical distribution of threshold temperatures, such that the non-ABC case, thresholds are distributed normally over (40,80), while ABCs increase the threshold for each individual by 20 degrees, resulting in a normal distribution over (60,100).

B Additional Figures and Tables

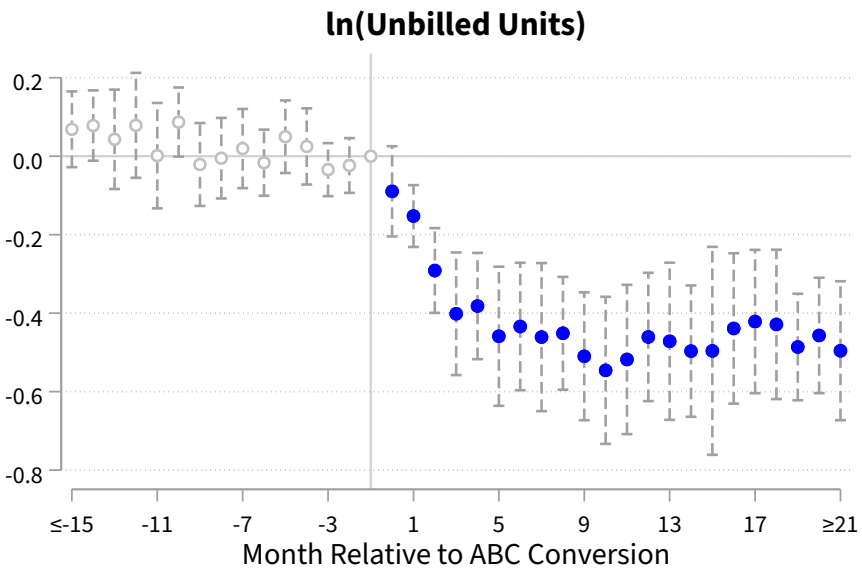


Figure B1: Dynamic Impacts of Theft-Resistance Cables on Unbilled Electricity Units

Notes: This figure displays the coefficients and their 95% confidence intervals from an event-study regression estimating the impact of theft-resistance cable installation on logarithm of unbilled electricity units, following Ahmad et al. (2024). Data are at the feeder level on a monthly basis. Regressions include IBC-by-month and feeder fixed effects. One month prior to the installation (-1) is the reference group, and the corresponding coefficient is normalized to zero. Standard errors are clustered at the feeder level.

References

Ahmad, Husnain F, Ayesha Ali, Robyn C Meeks, Zhenxuan Wang, and Javed Younas. 2024. "Down to the Wire: Leveraging Technology to Improve Electric Utility Cost Recovery." *Working Paper*.