Turning up the heat: Electricity infrastructure, temperature, and poor households*

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Abstract

This paper examines how utilities' efforts to improve service quality and cost recovery can affect households' ability to adapt to extreme temperatures. Using data on utility operations and electricity bills in Karachi, Pakistan, we find increased unbilled consumption (theft) with higher temperatures. We document how high temperatures and theft-resistant cables affect this household response to heat. The infrastructure upgrades theft, but their effectiveness declines in hotter months. Low-income households exhibit "comfort-smoothing" by reducing formal consumption on moderate days, while wealthier households maintain steady consumption. These findings highlight challenges in accessing cooling services and the unequal effects of infrastructure upgrades on climate-vulnerable communities.

Keywords: Electricity, Heat, Infrastructure, Losses
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1 Introduction

Global climate change is increasing temperatures, exposing the planet's population to more extreme heat. Households and firms can adapt to these changes, often through cooling services (for example, buying and using air conditioners). In high income countries, 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 live in low- and middle-income countries (LMICs) in tropical climates without air conditioning (Biardeau et al., 2020), and future adoption is predicted to remain concentrated among the wealthiest households (Davis et al., 2021). Although research highlights the limited resources available to the world's poorest communities to combat heat risks, little evidence exists on how these populations are currently adapting.[1]

Poor households in developing countries not only face financial barriers to purchase air conditioners but may also encounter higher costs for using electricity. This may translate into greater incentive for electricity theft as households resort to unmetered consumption to avoid high bills. On the supply side, reliable electricity supply also remains a challenge due to low cost recovery, insufficient investment, and overloaded infrastructure in many LMICs (Burgess et al., 2020; Carranza and Meeks, 2021). These competing interests present a major challenge in the developing context, one that is exasberbated by climate change; how to protect the poorest of the poor from extreme heat caused by climate change in a financially sustainable way? While utilities are investing in infrastructure upgrades to address financial viability, it remains uncertain how such improvements effect those most vulnerable to climate change.

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

In this paper, we investigate household adaptive responses to extreme heat and the role of electricity infrastructure upgrades in Karachi, Pakistan-one of the ten countries most severely affected by climate-related disasters. Specifically, we ask: How do low-income households adjust their electricity usage in response to high temperatures? Do infrastructure upgrades, designed to reduce electricity theft, affect electricity usage and losses differently under varying temperatures? What are the distributional consequences of these infrastructure improvements on households' ability to adapt to extreme heat? We expect that rising temperatures should increase electricity demand and theft, while theft-resistant cables reduce theft by raising the cost of illegal connections. As temperatures rise, the benefit of unauthorized connections goes up and households will find it attractive to resort to illegal connections despite the higher cost, reducing the effectiveness of the infrastructure upgrades.

To empirically analyze these effects, we combine gridded weather data with electric utility records on supply, billing, losses, and revenue recovery at the feeder-line level, as well as administrative billing data at the customer level, along with a household survey. A notable feature of the feeder-line level data is its ability to capture unbilled electricity consumption, which has historically been exceptionally high in Karachi. To address these issues, the electric utility launched a cable upgrade initiative in 2015, replacing bare wires with aerial bundled cables (ABCs) that make illegal connections through line puncturing more difficult. We obtain data on the staggered installation of theft-resistant cables across the city.

We then perform two primary empirical analyses using the 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 roll-out of cable upgrades is determined by pre-determined feeder-line losses and utility re-

source 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 yield several key results. First, based on feeder-line level data, we find that both billed and unbilled electricity consumption increase significantly as temperature rises; however, unbilled consumption is considerably more responsive, exhibiting sharper increases on hotter 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 their 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.

This 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 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 help fill a key gap in our understanding of 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). By 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 for research, given that utilities in low and lower-middle income countries often struggle with both cost recovery and reliable electricity service provision – 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 Section 7 concludes.

2 Background

Karachi, Pakistan provides a suitable setting for such a study, with respect to both extreme heat and poverty. As the largest city in Pakistan and the twelfth largest globally, it is home to 20 million people. Recent estimates indicate that 21.6% of national population is below the official poverty line (Barriga-Cabanillas et al., 2024).[2] Karachi's residents are 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 the 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 most effective ways residents can mitigate the adverse impacts 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 the 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, which prevented distribution companies from fully recovering costs. Widespread informal electricity use and poor bill recovery also undermined the 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]

[2]National poverty rate is 40% when using the global LMIC poverty line of $ 3.65 per day poverty line (World Bank, 2024)

[3]Ongoing reforms aim to eliminate electricity tariff subsidies and instead target support to low income

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 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, commonly 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, the bare wire infrastructure allows for quick reconnection. 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 were primarily aimed at reducing electricity theft, rather than improving the system's resilience to normal weather damage or extreme weather events, or reducing technical losses (Ahmad et al., 2024). The spatial and temporal variation in ABC installation creates a natural experimental setting for studying formal and informal household electricity usage during hot temperatures.

3 Conceptual Framework and Hypotheses

We motivate our research hypotheses through a simple model of a household's choice to engage in theft, or procure electricity formally. While mathematical derivations are relegated 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

households via the national social protection program (Profit, 2024).

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 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 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 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] 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.

[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.

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 levels. In addition, we collected survey data for a sample of utility customers, and utilize 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, therefore, represent the proportion of the electricity sent out that is not billed. Note that this is essentially 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 at 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 transform-

[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.

ers with theft-resistant cables installed relative to the total number of transformers in a feeder-line.

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 B1).

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 payments, and total monetary amount due to KE.

4.3 Weather

We utilize weather information from 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, direction, and more.

To combine the electricity and weather data, we match pole mounted transformers (PMTs) to weather records at the closest ERA5-Land grid node. For 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 customer-level analysis, we match customers to weather records at the PMT to whichthey belong to. After constructing the daily weather data for PMTs and feeder-lines, we aggregate the data to monthly level by summing the number of days over each billing month.Figure B2 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 $<21^{\circ}$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 $<21^{\circ}$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 electricity 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 lies in its ability to capture unbilled electricity consumption, which we measure as the difference between total electricity units sent out and billed units. This unbilled component is often overlooked in prior studies that rely solely on electricity bill data.

Figure 1 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 strong 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

[7] Unlike β_b, η_b is identified for all temperature bins, including the <21°C bin, because the timing of theft-resistance cable installation differs across transformers. Therefore, η_b for <21°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.

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, 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 may help 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. On one hand, the increased reliance on illegal connections can lead to higher losses, overburdened infrastructure, and further challenges for utility companies, exacerbating the overall inefficiencies of the system. On the other hand, these dynamics underscore the importance of addressing not just the supply and cost issues, but also the informal adaptations households may resort to in the face of extreme temperatures.

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 2 plots the coefficient estimates. The top panel shows the impact on customer bill complaints. We find that in months with more days of high temperatures, when electricity bills tend to be higher, there are 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 damages increases during hot temperature days. These findings reveal the various ways that customers may tamper the electricity distribution system and avoid high electricity bills during periods of extreme heat. This behavior stems from households seeking to avoid the financial burden of rising electricity bills due to increased demand for cooling appliances, particularly air conditioner.

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 3 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 B4 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 period of 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.

[8]In Appendix Figure B3, we replicate the results in Ahmad et al. (2024) but instead using the logarithm of total unbilled electricity units as the outcome variable.

Figure 4 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 on days with moderate temperature (i.e., <27°C). However, during hotter days when daily average temperature exceeds 27°C, the decline in electricity consumption 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 4 present the impacts on billed and unbilled electricity consumption, respectively. Consistent with Hypothesis 3, 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 cus-

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

tomers 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 formally connected previously.

Consistent with the hypothesis 4, during hotter days (above 27°C), the reduction in unbilled electricity consumption diminishes. This suggets that at higher temperatures, most customer's threshold for informal usage is crossed. As a result, customers may turn to alternative informal methods, such as meter tampering, to meet their persistent electricity needs for cooling appliances. This is partly confirmed by Figure 5, which shows the impact 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. Interestingly, while cable upgrades lead to a reduction in reported intentional wire damage, there is a slight increase in reported incidents of meter damage. This suggests 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 6 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°C), but increases in hot temperatures (>24°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 days to save on costs. This helps them manage potentially higher bills during hotter days, when informal consumption channels are less accessible, and their demand for cooling services is accurately billed.

Figure B5 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 their greater ability to afford higher electricity bills.

7 Conclusions

This paper explores how low-income households in Karachi, Pakistan, adapt to extreme heat in terms of electricity consumption, while also examining the role of infrastructure improvements aimed at reducing electricity theft. Our findings show that both billed and unbilled electricity consumption rise significantly as temperatures increase. However, unbilled consumption—an indicator of theft—shows a more pronounced increase, especially on extremely hot days. The installation of theft-resistant aerial bundled cables (ABCs) substantially reduces unbilled consumption, particularly on days with moder-

ate temperatures. However, this reduction was less effective during extreme heat, suggesting that households may find alternative ways to bypass the system when cooling needs become urgent. For formal utility customers, following the 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 underscore the need for suitable policies that 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 carefully designed to target the most vulnerable households. Implementing tiered subsidy structures based on verified income levels and electricity consumption patterns could prevent misuse while ensuring affordability. Direct cash transfers or a voucher system towards the consumption of electricity during peak summer months could help alleviate financial stress (Younas and Ali, 2022).

Other potential policy options include subsidizing energy efficient cooling solutions and promoting renewable energy alternatives, such as individual or community-based solar systems. These systems would reduce reliance on the main grid and provide an additional coping mechanism during extreme heat events. Although theft-resistant aerial bundled cables (ABCs) reduce unbilled electricity, extreme weather conditions may lead to alternative bypassing. Stronger enforcement, community monitoring, smart meters, and prepaid systems can enhance compliance and deter theft. Beyond energy measures, urban planning in densely populated cities like Karachi can mitigate extreme heat by expanding green spaces, increasing tree cover, using heat-reflective materials in residential buildings, and establishing public cooling centers for low-income communities. Future research can assess the feasibility and impacts of such policies to determine how best to support low-income households while maintaining a sustainable and reliable energy system.

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Figures and Tables

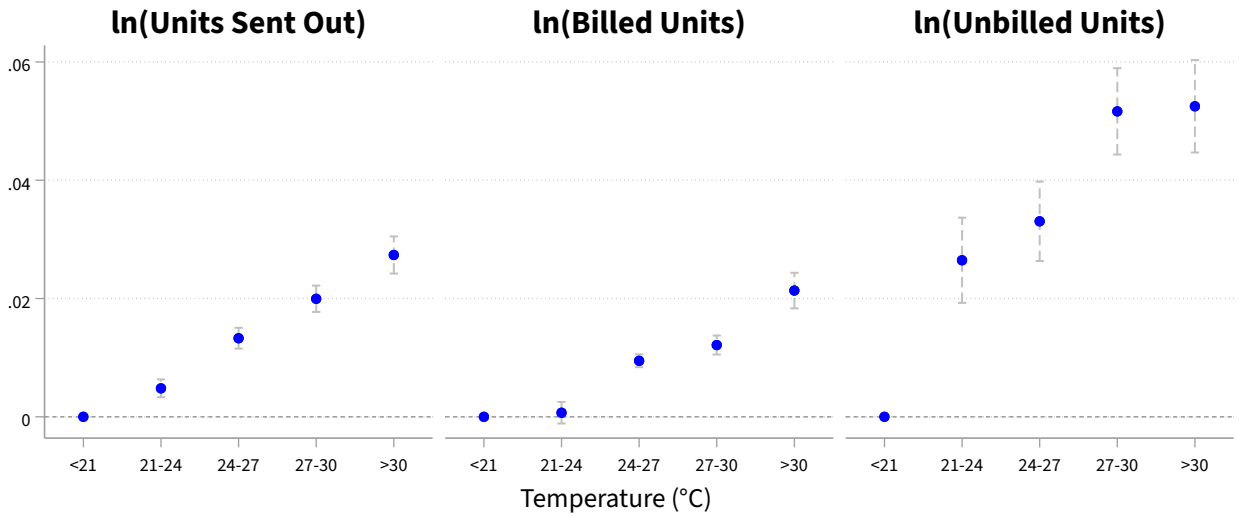


Figure 1: Heat and Electricity Consumption at the Feeder-Line Level

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.

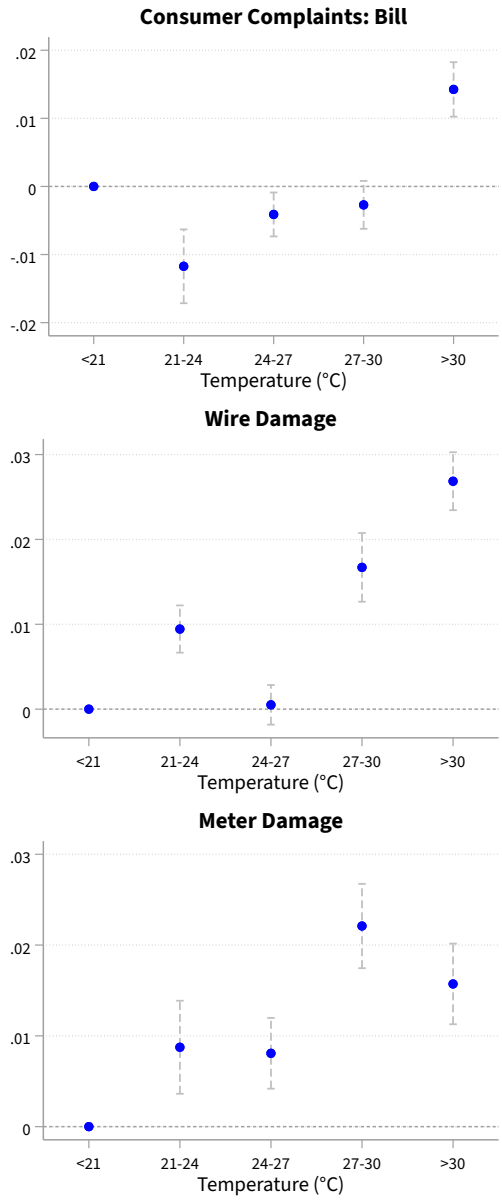


Figure 2: Heat, Consumer Complaints, and Infrastructure Damage

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.

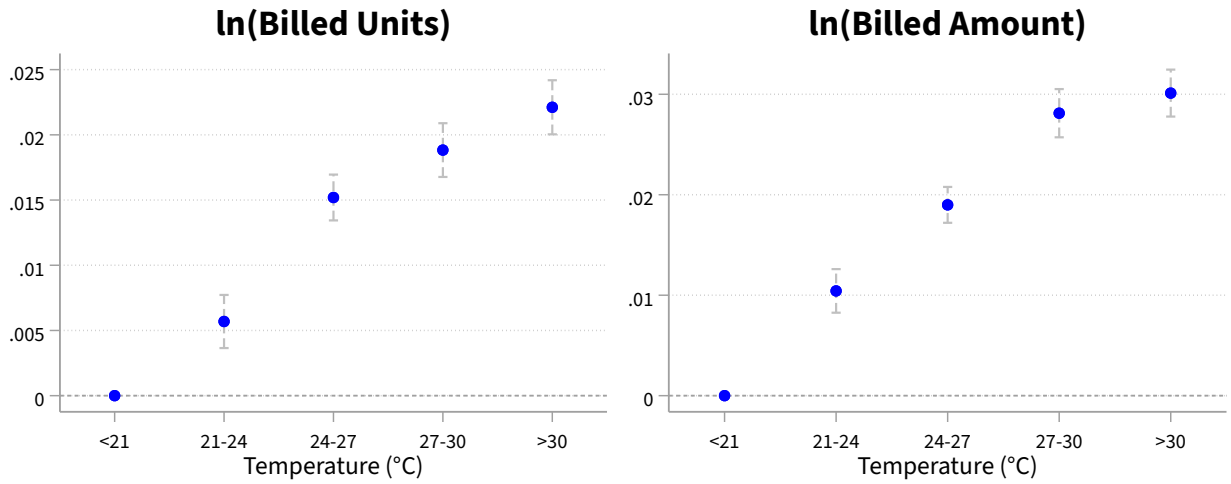


Figure 3: Heat and Billed Electricity Consumption of Formal Customers

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.

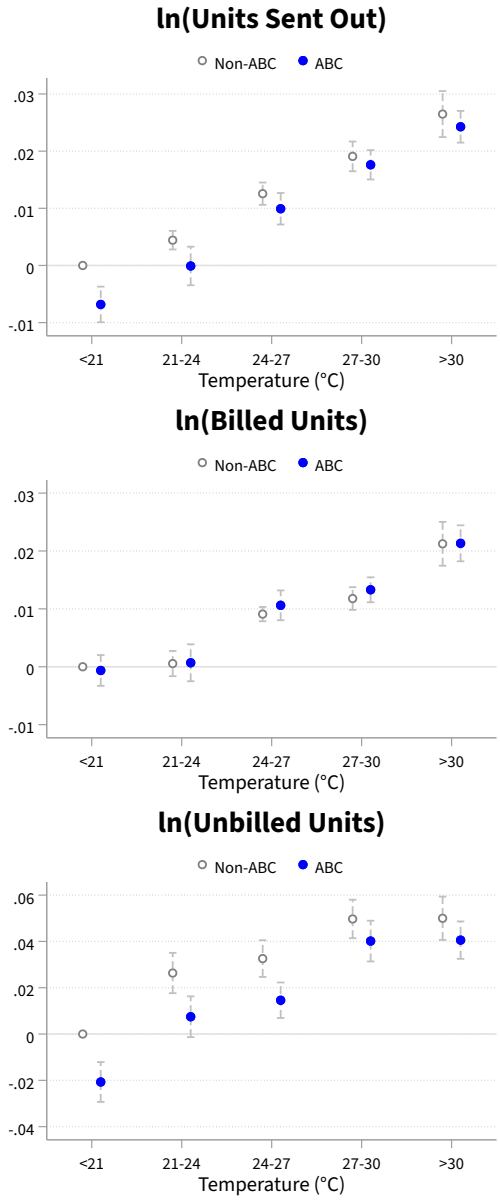


Figure 4: Heat, Theft-Resistance Cables, and Feeder-Line Electricity Consumption

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.

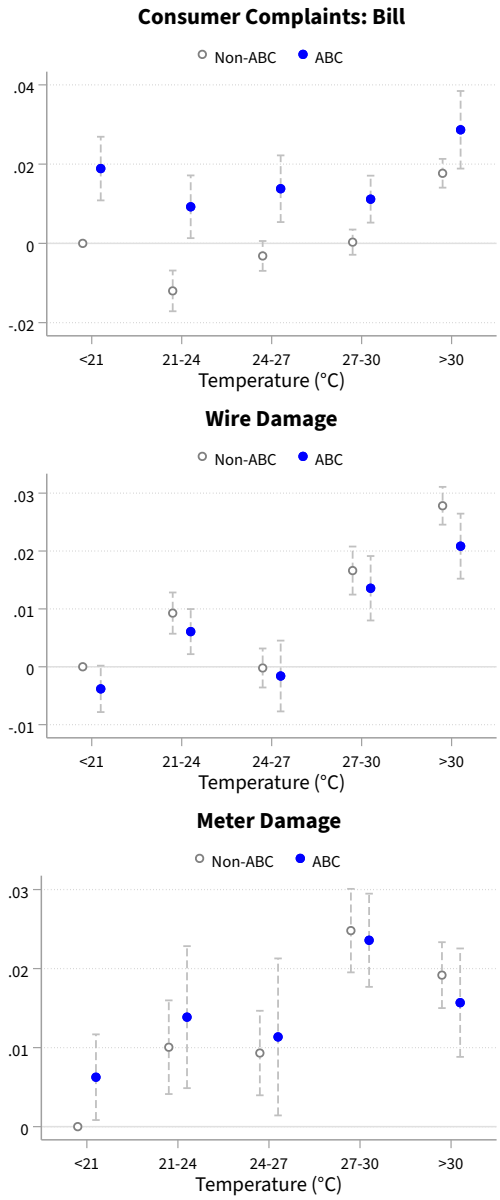


Figure 5: Heat, Theft-Resistance Cables, Complaints and Infrastructure Damage

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.

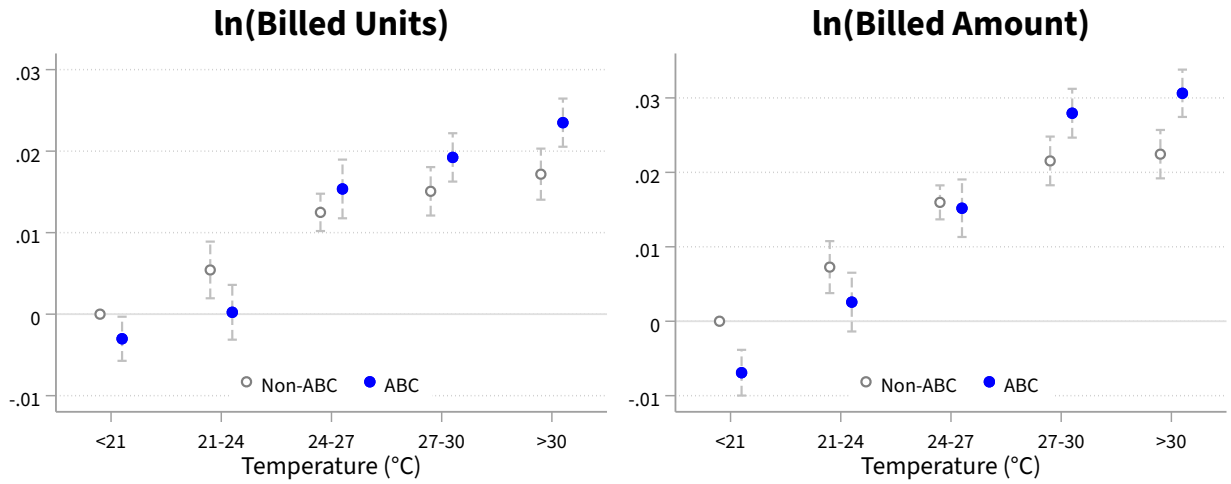


Figure 6: Heat, Theft-Resistance Cables, and Billed Consumption of Formal Customers

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.

Online Appendix

Turning up the heat: Electricity infrastructure, temperature, and poor households

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 scratch, 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 individuals 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 adjusting 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.

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 10 and 30 degrees. Further assume that when the feeder is converted to ABC wiring, the threshold value for each individual rises by 10 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.

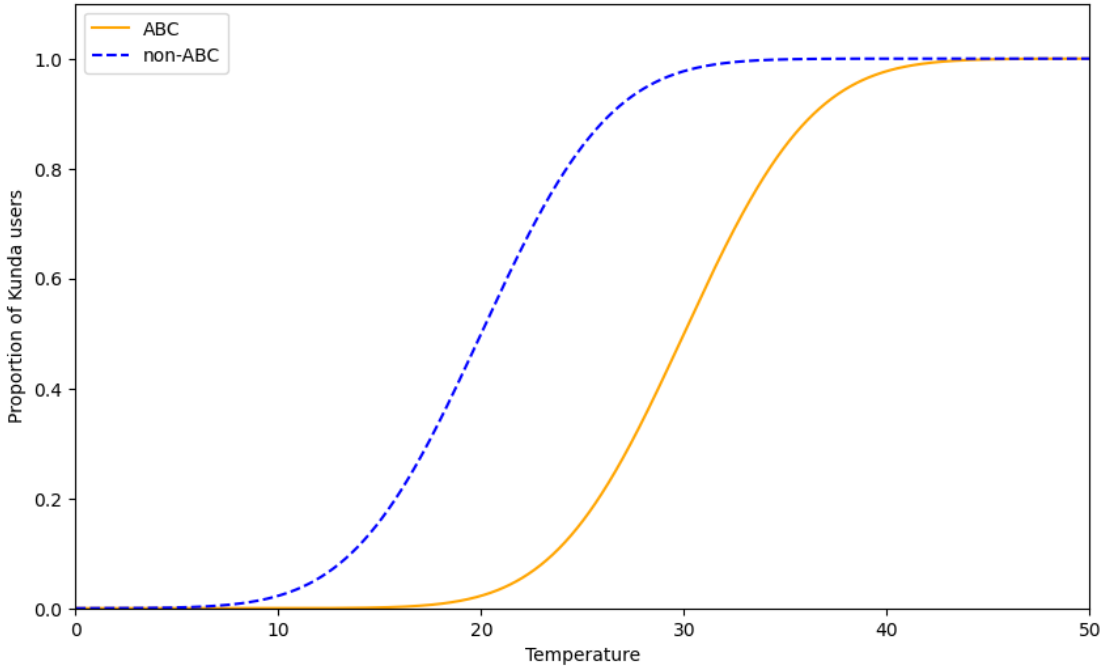


Figure A1: Illustration of shift in distribution of kunda useage with ABC installation

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

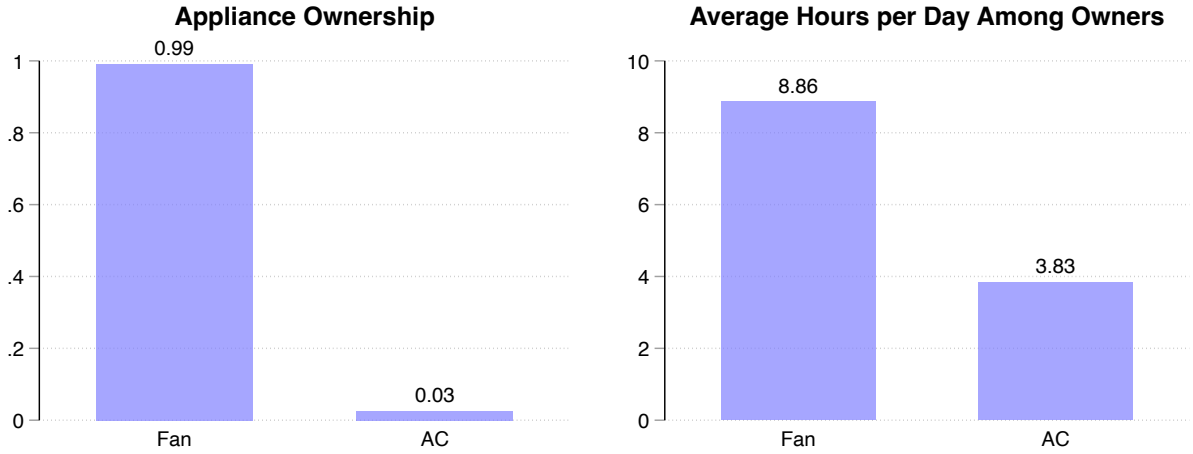


Figure B1: Self-Reported Cooling Appliance Ownership and Usage

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.

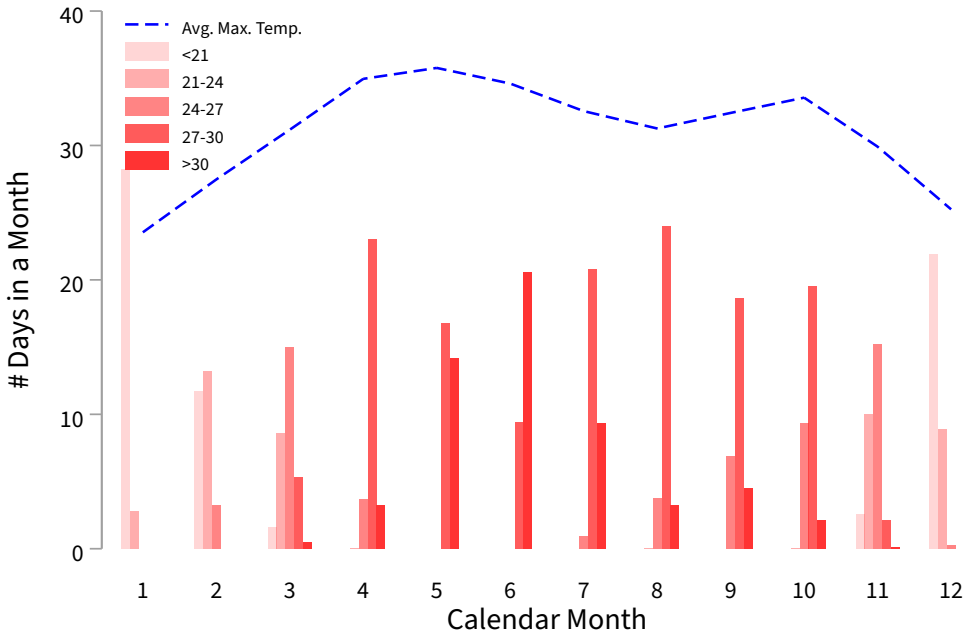


Figure B2: Distribution of Daily Temperature by Month

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.

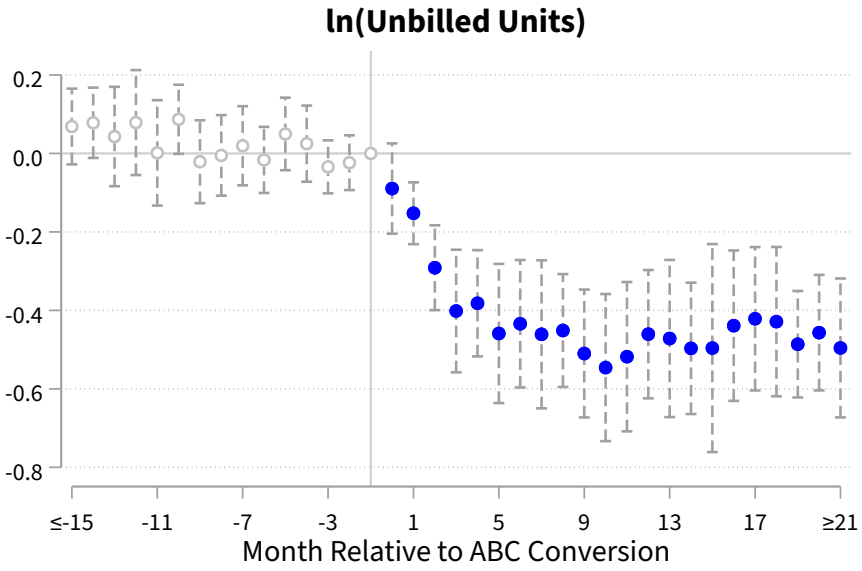


Figure B3: Dynamic Impacts of Theft-Resistance Cables on Unbilled Electricity Units

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.

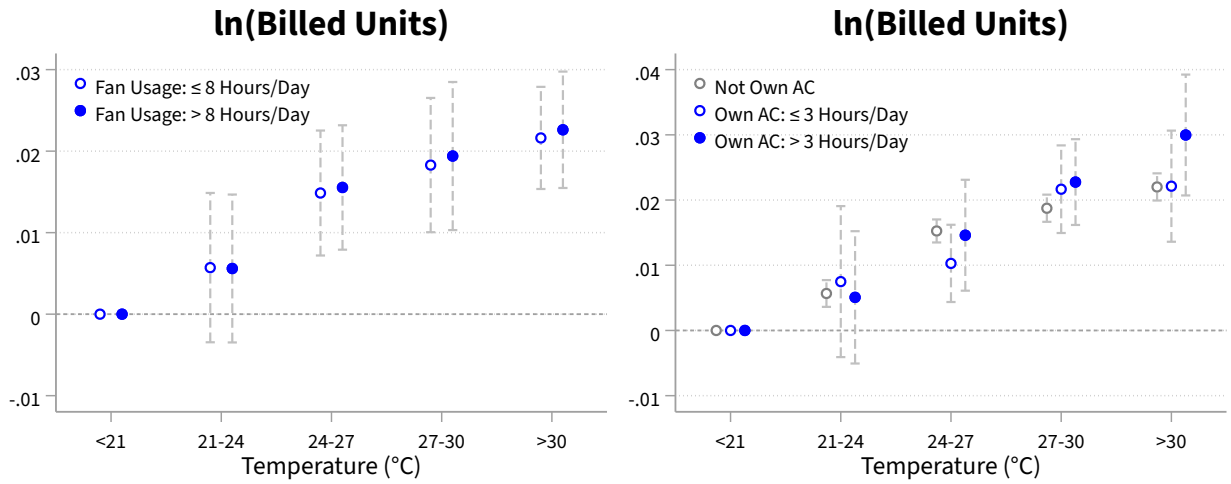


Figure B4: Heat and Customer-Level Billed Electricity Consumption by Appliance Usage

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.

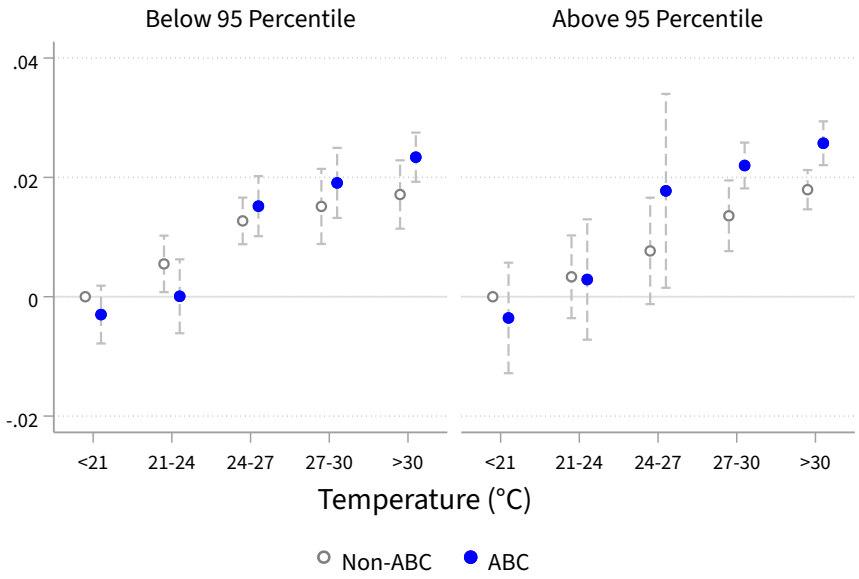


Figure B5: Heat, Theft-Resistance Cables, and Billed Units – Poor vs Rich

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.

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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*.