Efficiency and Equity Effects of Electricity Metering: Evidence from Colombia[*]

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Abstract

Many households in developing countries pay a fixed amount for their public utilities that does not depend on their consumption. This may lead to inefficiently high consumption and inequitable cost allocation. I study the change from fixed to volumetric tariffs for nearly 100,000 newly metered households in Colombia between 2010 and 2019. Consumption drops more than 25 percent after metering. However, this effect is heterogeneous across households, with the largest drop for high consumers. Individual metering increases consumer surplus for most households. These results are relevant for designing new tariffs with higher fixed charges to support the clean energy transition.

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1 Introduction

For many households in developing countries, electricity and water services are provided for a fixed fee that does not depend on usage. Consumption of these services might be unmetered, or there may be communal meters that measure the aggregate consumption at the neighborhood level, which is assigned equally across households. In either case, the absence of individual-level metering implies a zero (or close to zero) marginal price. This creates a problem of inefficiently high consumption, with potentially large welfare losses if the marginal cost of the utility service is high.

An interesting parallel in every country is the provision of digital services such as broadband internet, media streaming, and telephony. These services are typically sold to consumers for a fixed fee that does not depend on usage. The marginal price to the consumer of listening to another song or making another phone call is zero. Given that the marginal cost of providing these services exceeds zero, the fixed fee leads to inefficiently high consumption. Nonetheless, as long as the marginal cost is low enough, the welfare loss will be small.

In both cases, the primary concern of economists is the welfare loss due to pricing services below marginal cost. However, there are three objectives in designing public utility tariffs: providing efficient price signals, recovering costs for the utility, and fairly allocating these costs across consumers. A fixed charge not only fails to provide a signal for efficient consumption but also does not allocate costs across consumers in a manner that might be considered fair. This is because an unmetered household with high consumption will pay the same as an unmetered household with low consumption. Therefore, a tariff with only a fixed charge and no usage-based pricing is both inefficient and inequitable.

In this paper, I quantify the efficiency and equity effects of electricity metering in Colombia. I use administrative data for the universe of previously unmetered households that received an individual meter over the decade from 2010 to 2019—nearly 100,000 households in total. For these households, I observe the billing history during the period without a meter, during which time the amount that they paid for electricity did not depend on how much they consumed. In many cases, the billed quantities assigned to the households were an average of total neighborhood consumption measured at a communal meter. I then observe the billing history of the household after the meter installation when their electricity bill was calculated as a function of their consumption.

Since the 1990s, more than 90 percent of Colombian households have had an individual electricity meter. The previously unmetered households in my analysis tend to be from lower-income neighborhoods, often in marginalized communities. Electricity distribution utilities can assign neighborhoods in their service territories to one of three categories in which metering rates are low: (i) informal settlements with a decentralized and haphazard rollout of infrastructure, (ii) neighborhoods with high crime rates in which it is difficult for the utility to enter, and (iii) remote rural areas that are difficult to access. In the case of informal settlements, the use of communal meters to measure the total consumption of the neighborhood is common. These settlements qualify for additional subsidies, including a formalization program known as PRONE that upgrades the distribution network infrastructure and installs individual meters for each household. Most of the meter installations in my data occurred as part of these neighborhood-level upgrades funded by this formalization program.

There are three main findings from my analysis. First, billed electricity consumption falls by 26.5 percent after metering, with most of this decline occurring in the second and subsequent months after households receive their first bills showing their individual consumption. Payment rates increase, and outage duration declines after metering, consistent with metering being one component of a broader formalization program at a neighborhood level. Second, there is substantial heterogeneity in the consumption effects after individual meters are installed, with households in the high-usage quartile reducing their consumption by 47 percent over the first year, while households in the low-usage quartile significantly increase their consumption. Finally, individual meters increase consumer surplus for most households, with the households with the lowest consumption benefiting the most.

The effect of metering (and formalization more generally) is an important policy issue in the public utility sectors in many low- and middle-income countries. There have been major protests about the installation of meters—or the absence of meters—in many parts of the world. This is true even in Latin America, where metering rates are higher than in South Asia and Sub-Saharan Africa. In Colombia, there were 624,000 complaints to the public utility regulator about metering or estimated unmetered consumption in 2009, comprising 38 percent of all complaints. In Ecuador, 22 percent of dwellings connected to the electricity distribution network lacked an individual meter in 2010. Outside of Latin America, economists have studied unmetered electricity consumption in the agricultural sector in India, where zero marginal cost electricity has led to the overuse of groundwater pumping for irrigation (Fishman et al., 2016; Chakravorty et al., 2023).

More generally, the distributional effects that I estimate in this paper are relevant to the design of electricity tariffs to support the clean energy transition. Existing tariffs based on average cost pricing often exceed the marginal cost, even after including unpriced externalities (Borenstein and Bushnell, 2022). This problem will be exacerbated by the increased penetration of zero-marginal-cost renewable energy, which will further increase the gap between retail and wholesale electricity prices. One proposed solution is transitioning to tariffs with lower marginal prices and a larger fixed charge component. However, the distributional effects of such tariffs will look similar to the ones I find in this paper: households with low consumption will pay a disproportionate share of the service cost. Avoiding this problem will require the use of a mechanism to vary the fixed charge using a proxy for the household's willingness to pay for electricity (Burger et al., 2020; McRae and Wolak, 2021).

This paper contributes to the growing literature on the effects of investments in electricity distribution infrastructure in developing countries. The original focus for economists was on estimating the effects of electricity provision based on a dichotomous access measure (Dinkelman, 2011; Lee et al., 2020; Burlig and Preonas, 2024). Subsequent work has considered the effect of upgrades to local distribution grids to reduce voltage fluctuations (Berkouwer et al., 2023) or to reduce unauthorized connections and theft (Ahmad et al., 2024). Meeks et al. (2023) demonstrate that the installation of smart meters in Kyrgyzstan improved electricity quality and led to higher electricity consumption by allowing the utility to monitor the grid and quickly identify problems. Jack and Smith (2020) show how prepaid meters in South Africa reduced electricity consumption but still increased revenue by eliminating nonpayment problems.

In contrast to the existing literature which mostly ignores prices, the focus of this paper is on the effect of the higher marginal prices that are induced by the meter installation. As such, it contributes to the small literature on the transition from fixed to usage charges. The closest related paper is Ito and Zhang (2020), who study the transition from fixed charges to consumption charges for district heating services provided to households in Tianjin, China. Like my findings, they estimate an overall reduction in heating usage but heterogeneous effects across households, with low users increasing their consumption under the new tariff. Nevo et al. (2016) use detailed information on household data usage to compare fixed and usage-based charges for broadband internet usage.

The remainder of the paper is organized as follows. In Section 2, I provide a simple illustrative model to frame the analysis of the effects of metering. In Section 3, I describe the data used for the analysis. Sections 4 and 5 contain the empirical analysis of the average and heterogeneous metering effects. Section 6 concludes.

2 Illustrative model

Figure 1 illustrates the effect of providing individual meters in a neighborhood with N households sharing a single meter. Total monthly electricity consumption in the neighborhood is $N\bar{q}$. Each household is billed for an equal share of total consumption, $\bar{q}$. The regulated price of electricity, P, is set to recover the firm's total fixed costs and the constant marginal cost of electricity c.

With N sufficiently large, the effect of one additional consumption unit on an individual household's bill is negligible. This is because the additional consumption is divided among all N users, so the bill will increase by P/N. In effect, the marginal price of consumption for the unmetered household can be treated as zero. The figure shows the demand for a representative low-consumption household, $D^L(P)$, and a representative high-consumption household, $D^H(P)$. Because the marginal price is zero, the low-consumption household consumes $q_1^L = D^L(0)$, and the high-consumption household consumes $q_1^H = D^H(0)$.

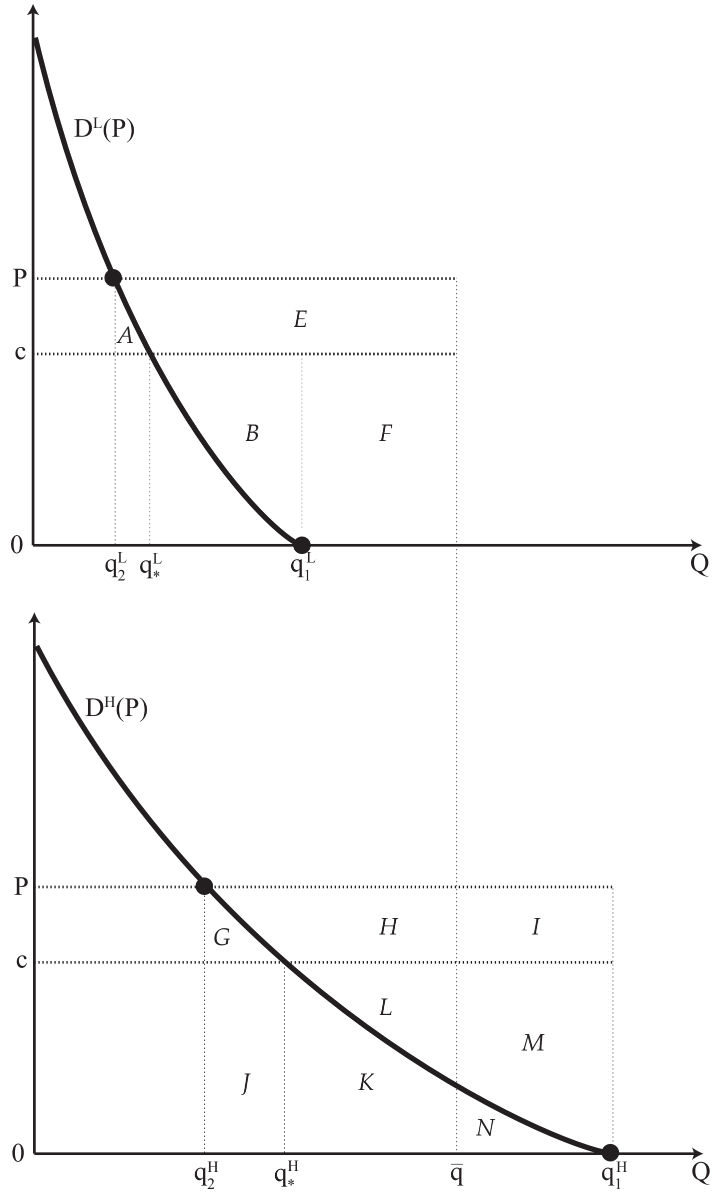
The low-consumption household would be better off with no electricity than it would be receiving electricity and paying for the unmetered connection. This is because the monthly bill $P\bar{q}$ exceeds the area under the demand curve $D^L(P)$.

Consider the effect of providing metered connections to the unmetered households in the diagram. With a meter, the marginal price increases from zero to P. Given the higher marginal price, the consumption of the low-consumption household will decrease from q_1^L to $q_2^L = D^L(P)$. Welfare increases by the area B less the area A. In effect, the meter causes the marginal price faced by the household to increase from an inefficiently low level (zero) to an inefficiently high level (greater than marginal cost).

The high-consumption household consumes q_1^H, exceeding the quantity they pay for, $\bar{q}$. Based on the diagram, the high-consumption household is better off with the unmetered connection than it would be without any connection. After the meter installation, their consumption falls from q_1^H to q_2^H. However, the meter installation also makes the high-consumption household better off. This is because the marginal benefit of the units of consumption between q_2^H and q_1^H is low (area $G + J + K + N$) relative to the additional cost for the unmetered connection (area $G + H + L + J + K$). Consumer surplus increase by area $H + L - N$ with the meter. Overall welfare increases by the area $L + M - G$.

The discussion so far ignores the cost of the meters (which may be large compared

Figure 1: Stylized consumption and welfare effects of metering



to the welfare gains). It also does not consider the effect on the firm of the reduction in revenue due to the decline in consumption. If the price had been set to recover the firm's fixed costs exactly, then the regulated price may need to be raised. This would make all customers worse off. The assumption for the analysis is that the metering project only covers a small number of connections so that the effect on revenue (and any regulatory adjustments to price) is negligible.

3 Data

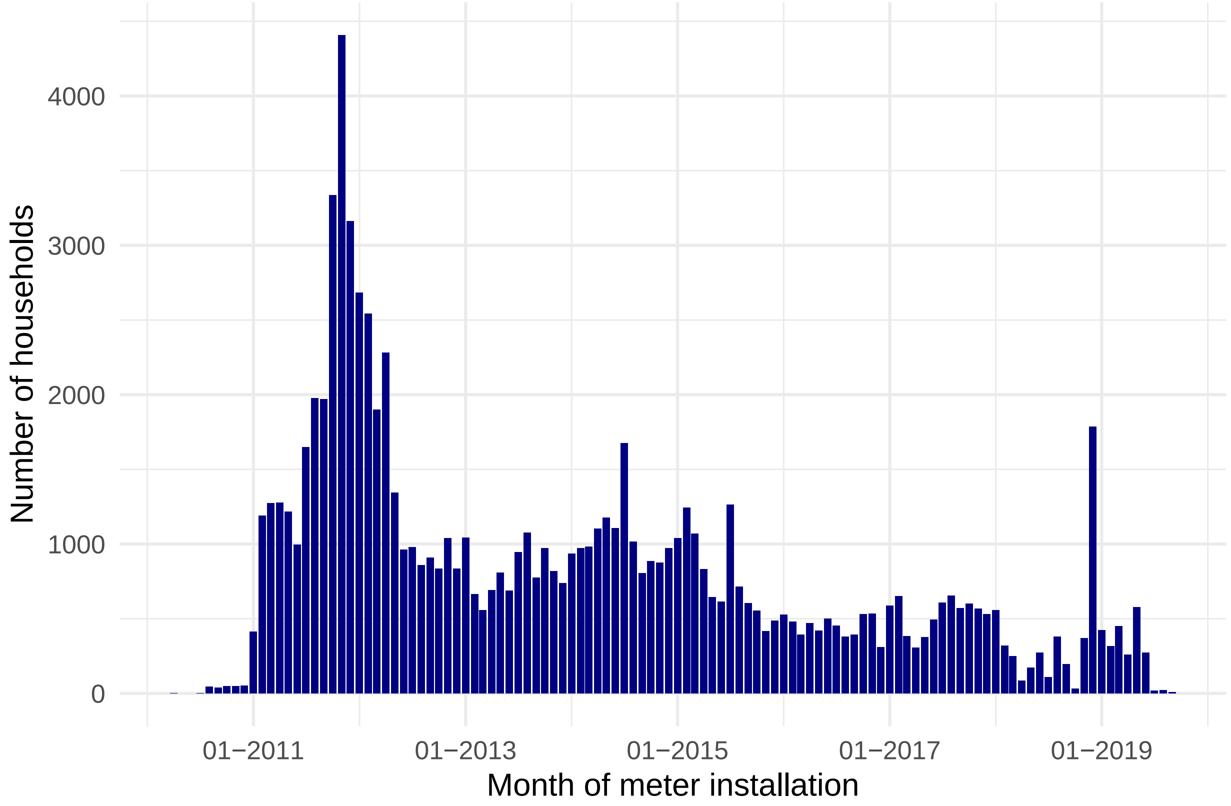
I study the effect of electricity metering on the entire population of Colombian households who were previously unmetered and received an electricity meter between late 2010 and mid-2019. I restrict the analysis to households with at least six months of billing history without a meter, followed by at least six months of billing history with a meter. That is, I only focus on existing connections that are upgraded to have a meter rather than new connections that have a meter from the beginning. I exclude the small number of households that were unmetered, metered, and reverted to being unmetered.

Based on these sample criteria, I construct a sample of 95,354 newly metered households. The meter installation date for the sample households varied from 2010 until 2019, although a higher share of installations occurred in the first two years of the sample period (Figure 2).

Figure 3 shows the location of the newly metered households in the sample. Each circle is the centroid of a Colombian municipality (equivalent to a county), with the circle size corresponding to the number of household observations in that municipality. While there is considerable geographic diversity, and most Colombian municipalities are represented in the dataset, most of the sample comes from informal settlements in large cities such as Medellín and Calí, as well as small and large cities in the southwestern and northern Caribbean regions of Colombia. The municipality with the largest number of observations (7 percent of the sample) is Tumaco on the southern Pacific coast. The ten municipalities with the largest number of observations comprise about 28.9 percent of the total sample.

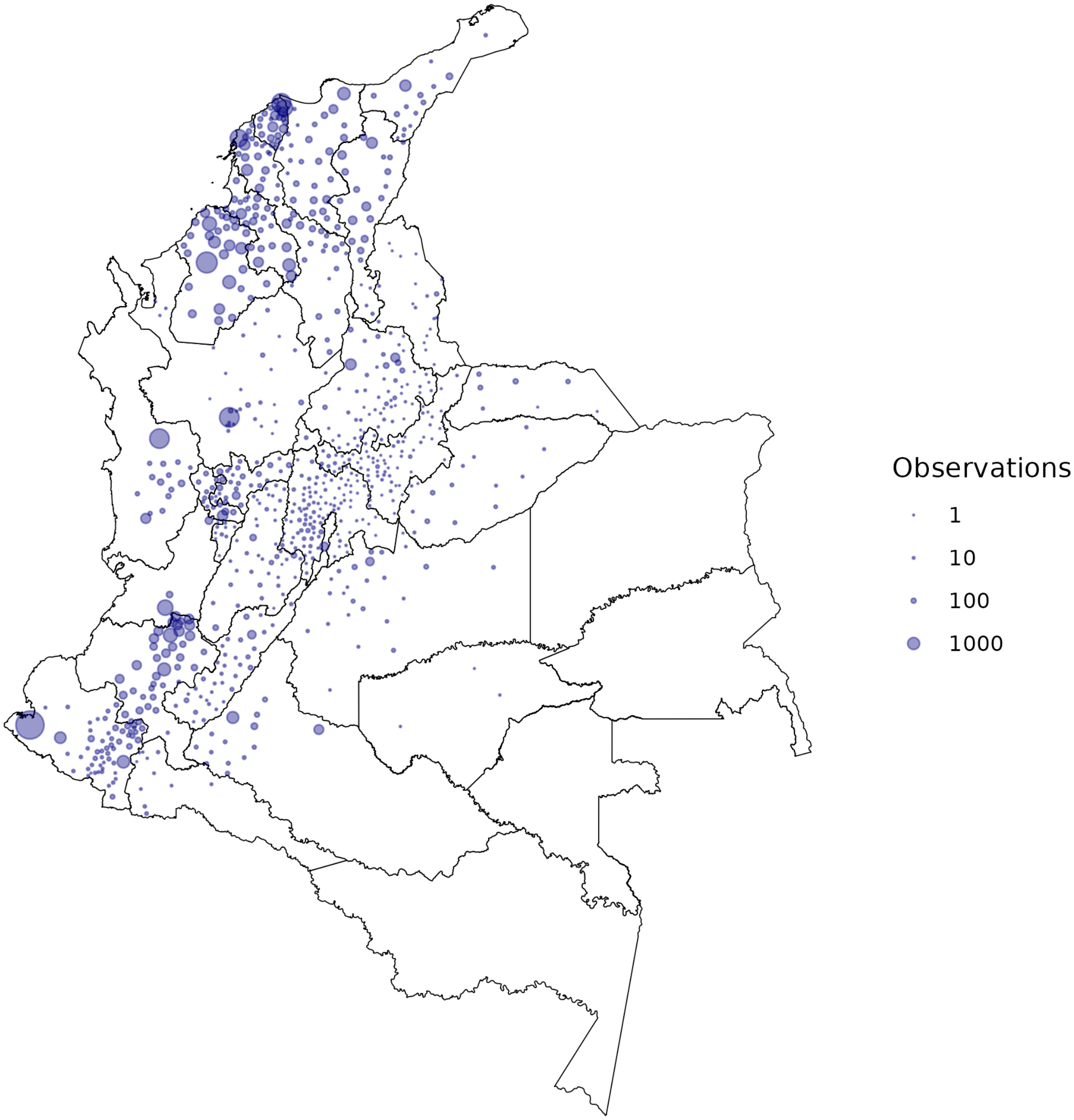
For the empirical analysis, I constructed two sets of control groups for the newly metered households. The first is the full population of unmetered households who remain unmetered throughout the entire sample period ("always unmetered"). There are 387,206 such households in Colombia during the 2010 to 2019 sample period. The second control group consists of the households at the electricity transformers as the newly metered

Figure 2: Month of meter installation for newly metered households in the sample



Notes: The figure shows the number of previously unmetered households each month that received an electricity meter.

Figure 3: Location of newly metered households, 2010-2019



Notes: Each point shows the centroid of a municipality in the dataset. The size of the point corresponds to the number of households that switch from being unmetered to metering during the 2010 to 2019 sample period.

households who always have a meter throughout the sample period ("always metered"). There are 1,154,177 households in this group.

For all households in the treatment and control groups, I used the full electricity billing history between August 2010 and December 2019.[1] This dataset includes the municipality, stratum (a neighborhood classification used for assigning tariffs), transformer identifier, billed consumption in kilowatt-hours, start date and length of each billing cycle, the tariff components, and a breakdown of the total bill, including the consumption charge, subsidies, and overdue amounts. I merge this data with a separate transformer-level dataset with the technical characteristics of each transformer and the monthly number and length of outages at the transformer. This dataset provides a uniquely detailed panel spanning nearly a decade and covering the billing periods before and after the installation of meters for nearly 100,000 Colombian households.

4 Average effects of metering

4.1 Empirical methodology

I use an event study framework to estimate the household-level mean effects of installing an electricity meter. The treated observations are those households with at least six months of electricity bills with unmetered quantities, followed by a meter installation and then at least six months of metered quantities. The time period $t = -1$ corresponds to the last unmetered electricity bill, and $t = 0$ corresponds to the first metered bill. That is, the meter installation occurs between periods -1 and 0.

In this setting, the treated households are the ones with meters, and the control households are the ones without meters. Meter installation is assumed to be an absorbing state, with the small number of households that revert to being unmetered dropped from the sample. A potential concern in this setting is the staggered meter installation that changes the composition of the control group between the beginning and end of the sample. If there is heterogeneity in the effect of meter installation, this change in the composition of the control group can seriously contaminate the estimated treatment effects (Sun and Abraham, 2021).

To address this problem, I made two changes. First, I supplemented the control group by including all never-metered households. These are the households that only

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[1] The panel is unbalanced as some households enter the sample between 2010 and 2019, while others drop out of the sample.

received electricity bills with unmetered quantities throughout the sample period. That is, the control observations comprise both the not-yet-metered and the never-metered households.

Second, I follow the two-step methodology of Gardner (2022) and Borusyak et al. (2024). The first step of this methodology estimates the household and time fixed effects using only the unmetered observations (Equation (1)).

$$y_{it} = \alpha_i + \gamma_{rt} + \varepsilon_{it} \tag{1}$$

Here the outcome variable y_{it} is defined for household i in month-of-sample t. The α_i is a household fixed effect, and the γ_{rt} is a region-by-month-of-sample fixed effect. In the base specification, the region is a distribution network territory.

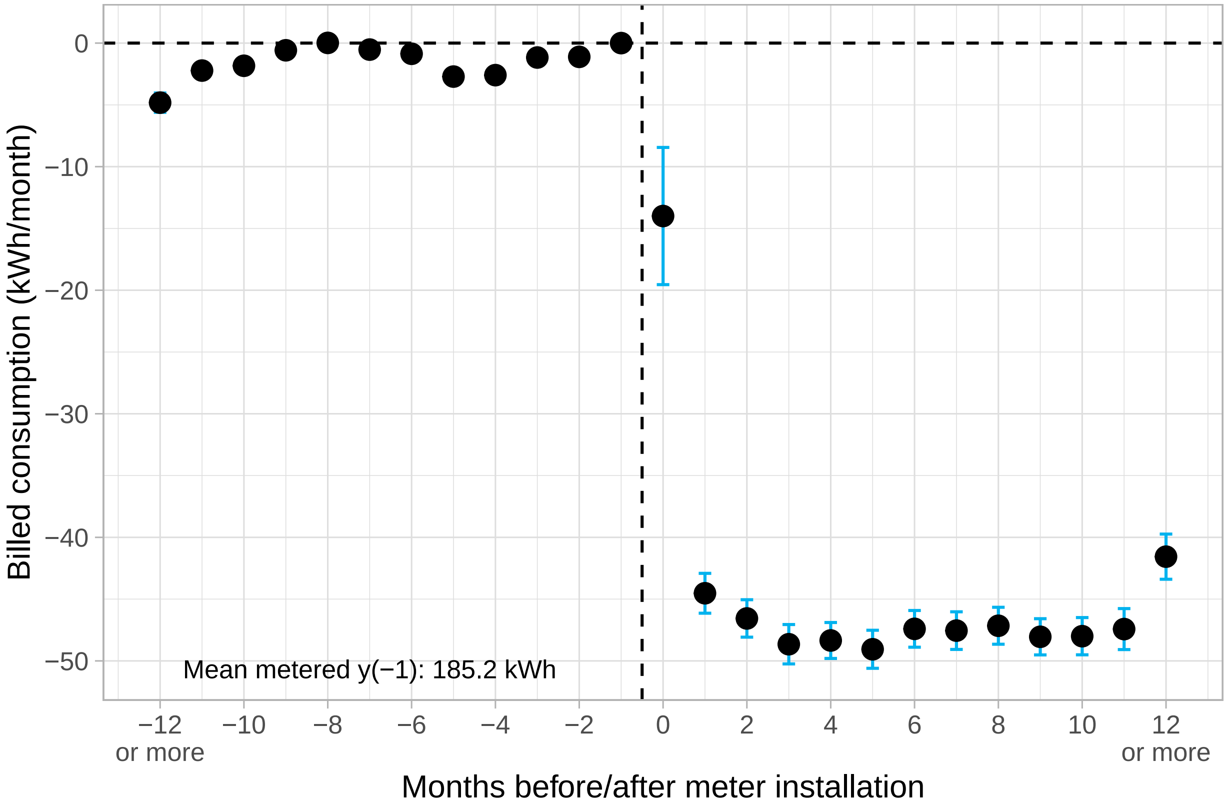
I then use Equation (1) to predict the residuals (that is, the difference between the outcome y_{it} and the unit and time fixed effects) for the full sample, including both the metered and unmetered observations. I regress these residualized outcomes on relative event time indicators (Equation (2)).

$$\tilde{y}_{it} = \sum_{\substack{k=-12 \\ k \neq -1,\infty}}^{12} I[t_{it} - T_i = k] + \varepsilon_{it} \tag{2}$$

In this equation, $\tilde{y}_{it}$ is the residualized outcome for household i in month-of-sample t. Household i has a meter installed in period T_i. The event time indicators for household i run for twelve months before and after meter installation. The indicator at -12 includes all observations twelve or more months before the installation, and the indicator at 12 includes all observations twelve or more months after the installation. The event time for the never-metered households is set to be ∞. The two excluded event time indicators are -1 and ∞. That is, all of the effects are measured relative to the outcome in the last unmetered month before meter installation.

I estimate this model for five outcome variables: the household's billed consumption in kWh per month, the total bill for the consumption in Colombian pesos, the government subsidy transfer included in the total bill, an indicator variable for the household being overdue on their electricity account, and the monthly minutes of outages at the household's transformer.

Figure 4: Mean effect of meter installation on billed electricity consumption



4.2 Results

The first event study results show the effect of meter installation on the quantity of electricity on the household's monthly electricity bill (Figure 4). For the period before meter installation, this quantity will be an estimate or an allocation of the metered quantity at a shared communal meter. After meter installation, this quantity will be the individual electricity consumption of the household each month as measured by the meter.

The mean billed consumption in the month before meter installation was 185.2 kWh. While the coefficients on the pre-event indicators are statistically significantly different from zero, they show no obvious trend and are small in magnitude, varying between -4.82 and 0.02 kWh.

In the month after meter installation, the first metered quantity falls by an average of 14.0 kWh, or 7.6 percent of the pre-metered billed consumption. This relatively small decline is consistent (i) with all households receiving an equal allocation from communal meters before the installation of individual meters and (ii) no behavioral response by households until they receive their first metered electricity bill. The measurements at communal meters will include all technical and non-technical losses between the upstream meter and the point of entry to each dwelling. These losses are allocated to the unmetered households in the pre-event period but are borne by the distribution company after meter installation.

The largest decline in the metered quantity occurs in the second month after the meter installation. Billed (and actual) consumption falls by a further 30.5 kWh per month or 16.5 percent of the pre-metered billed consumption. This decline is more likely to capture the behavioral response of households once they have received information about their true consumption and how it is used to calculate their electricity bill. There is an additional small decline in subsequent months to a maximum drop of 49.1 kWh per month (26.5 percent of the pre-metered billed consumption) five months after meter installation. In the long run, more than 12 months after meter installation, the magnitude of the overall decline reduces slightly to 41.6 kWh per month.

The decline in mean consumption after metering is consistent with households adjusting their electricity consumption behavior in response to an increase in the marginal price of consumption (from zero to some higher price). The overall decline of 26.5 percent is consistent with previous empirical evidence for the change in consumption from metering, mostly from smaller-scale studies. Casillas and Kammen (2011) study the installation of individual meters in two non-grid-connected villages in Nicaragua that rely on diesel generation. They found that the total load fell by 28 percent after metering. A case study of regularization of electricity service for a *favela* in Sao Paulo, including metering and billing, found that electricity consumption fell by 23 percent even before implementing an energy efficiency program (USAID, 2009). Munley et al. (1990) analyze an experiment in which some residents of a newly-submetered apartment complex began to pay for their own electricity while a control group continued to receive electricity included in their rent. The mean consumption of the users who were paying for their electricity was 24 percent lower. In a similar setting, Dewees and Tombe (2011) find that electricity consumption declined by 20 percent in a Canadian condominium complex after introducing sub-metering.

The second set of results (Figure 5) shows the effect of meter installation on the electricity consumption subtotal and the subsidy transfer component of the electricity bills, both measured in Colombian pesos.[2] The mean bill subtotal for the not-yet-metered households,

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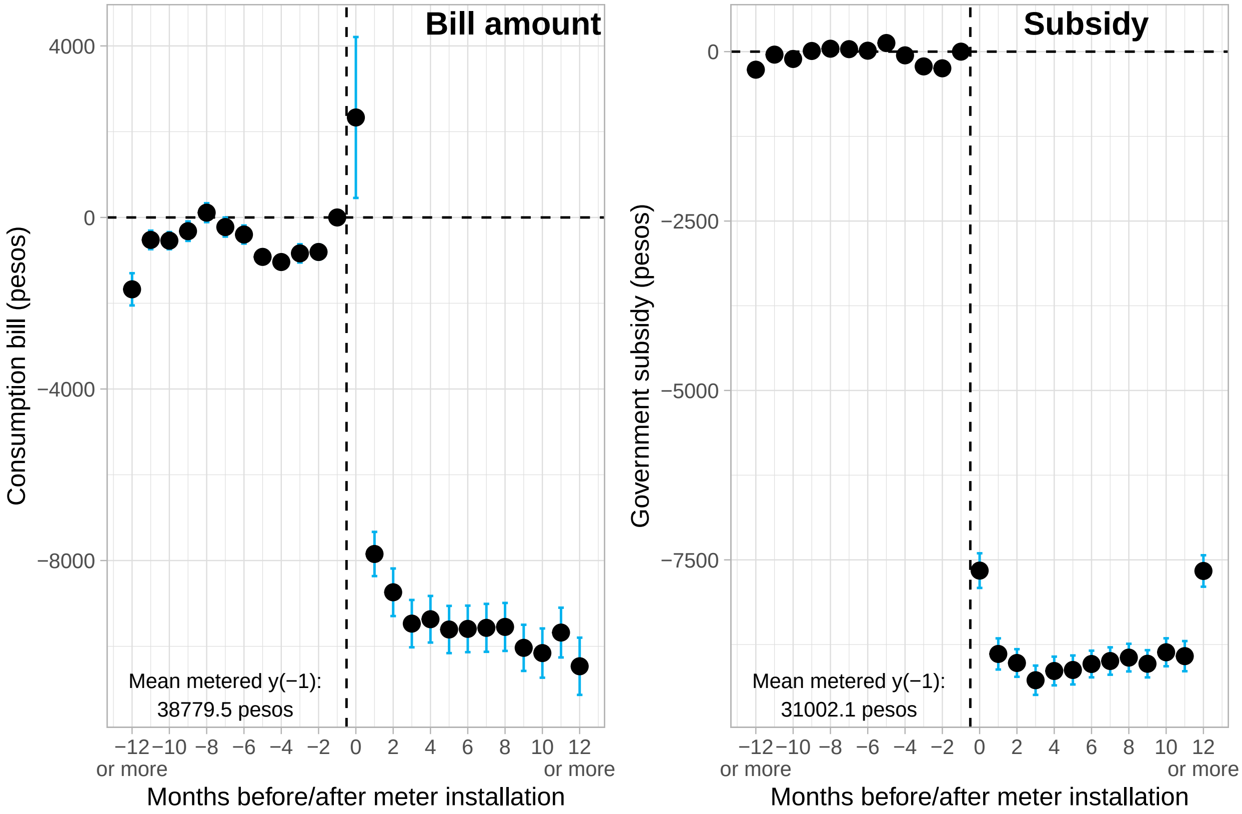
[2] The electricity consumption subtotal may differ from the total bill amount because the latter includes overdue

Figure 5: Mean effect of meter installation on consumption bill and subsidies



one month before meter installation, was 38,800 pesos (US$15.70). This amount is what is owed by the household after deducting the subsidy transfer. The pre-event coefficients for this variable show a similar pattern to those in Figure 4, but no overall upward or downward trend.

The subsidy transfer component of the bill for the not-yet-metered households, one month before meter installation, was 31,000 pesos (US$12.55). The total billed revenue for the electricity distributor is the sum of the consumption charge and the subsidy transfer: 69,800 pesos (US$28.26) one month before meter installation.

The immediate effect of the meter installation has opposite effects on the consumption charge and the subsidy transfer. The former increases by 2331 pesos (6 percent). The latter decreases by 7658 pesos (24.7 percent). These results are consistent with the expected effect of metering in a setting like Colombia with an increasing block tariff. Most households pay a subsidized price for the first block of electricity consumption (either 130 kWh or 173 kWh per month), then pay the regulated base tariff for subsequent consumption.

Consider a stylized example of two households, one with a consumption of 100 kWh and another with a consumption of 300 kWh. Suppose the base tariff is 20 cents/kWh, and there is a subsidy of 50 percent for the first 200 kWh of consumption. With a communal meter, total consumption is 400 kWh, and both households would be billed for 200 kWh. The mean bill will be $20, and the mean subsidy transfer will be $20. With individual meters, the first household will have a bill of $10, incorporating a subsidy transfer of $10. The second household will have a bill of $40, incorporating a subsidy transfer of $20. The mean bill increases by $5 to $25, and the mean subsidy transfer declines by $5 to $15. Even though aggregate consumption stays the same, the aggregate subsidy transfer declines because the loss of the subsidy for the low-consuming households is not replaced by additional subsidy for the high-consuming households.

The consumption subtotal declines by 10,177 pesos (US$4.12) in the second month after meter installation, compared to the first month. This fall corresponds to the large drop in metered consumption in the second month after meter installation (Figure 4). In contrast, there is only a relatively small decline of 1230 pesos in the subsidy transfer. These two results suggest that most of the drop in consumption occurs for unsubsidized consumption above the subsidized quantity threshold.

The overall decrease in the subsidy transfer of about 9000 pesos (29 percent) relative to the baseline unmetered subsidies demonstrates a public finance benefit of metering

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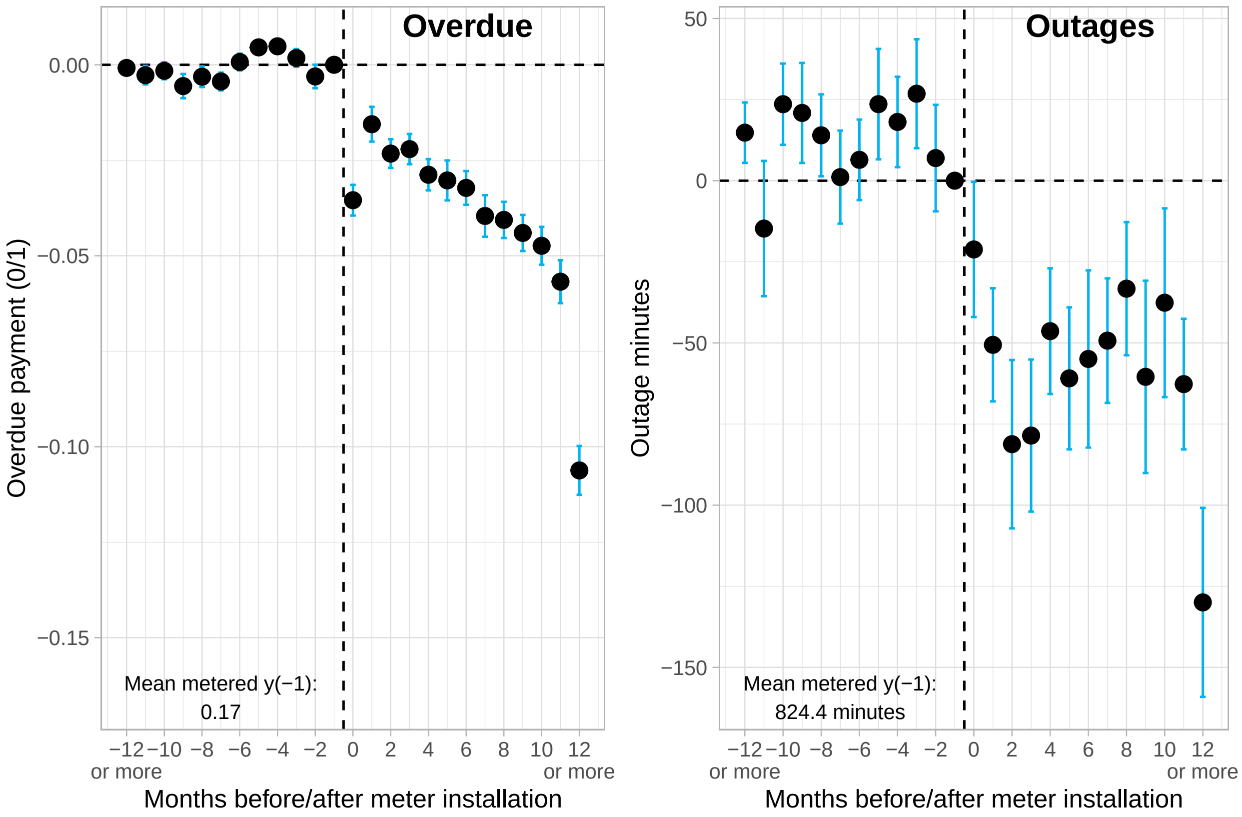
amounts from other months, adjustments to previous months, and other charges.

Figure 6: Mean effect of meter installation on overdue amounts and outages



in the presence of increasing block tariffs. For this type of tariff, billing households for a community-level average consumption will require larger subsidy transfers to compensate for lower initial prices. This is because the unsubsidized consumption of high-use households will offset the “wasted” subsidies of low-use households whose consumption is below the quantity threshold.

The final set of event study results (Figure 6) show the effects of metering on two other outcomes of interest: payment rates and distribution network outages. For unmetered households immediately before meter installation, 17 percent have an overdue balance on their electricity bills. The pre-event coefficients are close to zero (although mostly significantly different from zero) but show no obvious increasing or decreasing trend. There is a 3.5 percentage point drop in overdue rates in the month after meter installation, though more than half of this drop is reverted in the second month. In subsequent months, the overdue rates for the newly metered households show a declining trend relative to the never-metered households, eventually falling by nearly 6 percentage points (or 33 percent relative to the baseline). Overdue rates are even lower in the long run more than 12 months after meter installation: 10.6 percentage points lower than the baseline of 17 percent).

There are two possible reasons why newly-metered households are more likely to pay their electricity bills than never-metered households. First, the amount of the electricity bill is lower on average (Figure 5). Households have a greater capacity to pay a smaller bill. Moreover, the bill amount will fall the most for households with the lowest electricity consumption. Given the correlation between income and electricity consumption, these are exactly the households that are most likely to have difficulty paying a large bill. Second, new metering technology may make it easier to enforce payment by allowing non-payers to be remotely disconnected. Instead of sending a technician to the dwelling to manually disconnect the households, the electricity distribution company can remotely disconnect and reconnect the user.

Regarding electricity reliability, the newly metered households had an average of nearly 14 hours of outages in the month before meter installation. The pre-event coefficients are mostly positive and individually statistically significant, suggesting that neighborhoods with more unreliable electricity supply are somewhat more likely to be upgraded and have meters installed. Outages for the metered households fell by about one hour per month during the first year after meter installation, with an effect size more than twice as large in the long run. This improvement in reliability likely reflects the result of upgrades to the local distribution network that occurred at the same time as the meter installation.

All else being equal, increased electricity reliability will increase a household's electricity consumption. However, given that the average improvement is relatively small—a drop of about two hours of outages per month— the change in pricing incentives for the household will overshadow this effect.

5 Heterogenous effects of electricity metering

The results in the previous section provide estimates of the mean effect of electricity metering on households. However, these mean effects mask substantial heterogeneity in the metering experience for individual households. Households with high, but previously unobserved, consumption will face a large increase in their electricity bills after metering. Conversely, households with low consumption will see a large decrease in bills.

5.1 Consumption effects by quartile

For each newly metered household, I calculate the difference between their metered consumption in the first month after metering and the mean metered consumption of the households at the same transformer. I then divide the households into four groups based on the quartiles of this difference. For the quartile 1 households, their electricity consumption is substantially lower than the average of their neighbors. These households will likely experience a drop in their electricity bills after metering. Quartile 4 households are those with substantially higher electricity consumption compared to their neighbors. They will likely experience an increase in their electricity bills after metering.

I estimate the evolution of metered electricity consumption for the four quartiles in the months after the meter installation. Specifically, I estimate Equation (3) separately by quartile:

$$\log(q_{it}) = \sum_{k=1}^{12} \beta_k I[t_{it} - T_i = k] + \alpha_i + \gamma_{rt} + \varepsilon_{it} \tag{3}$$

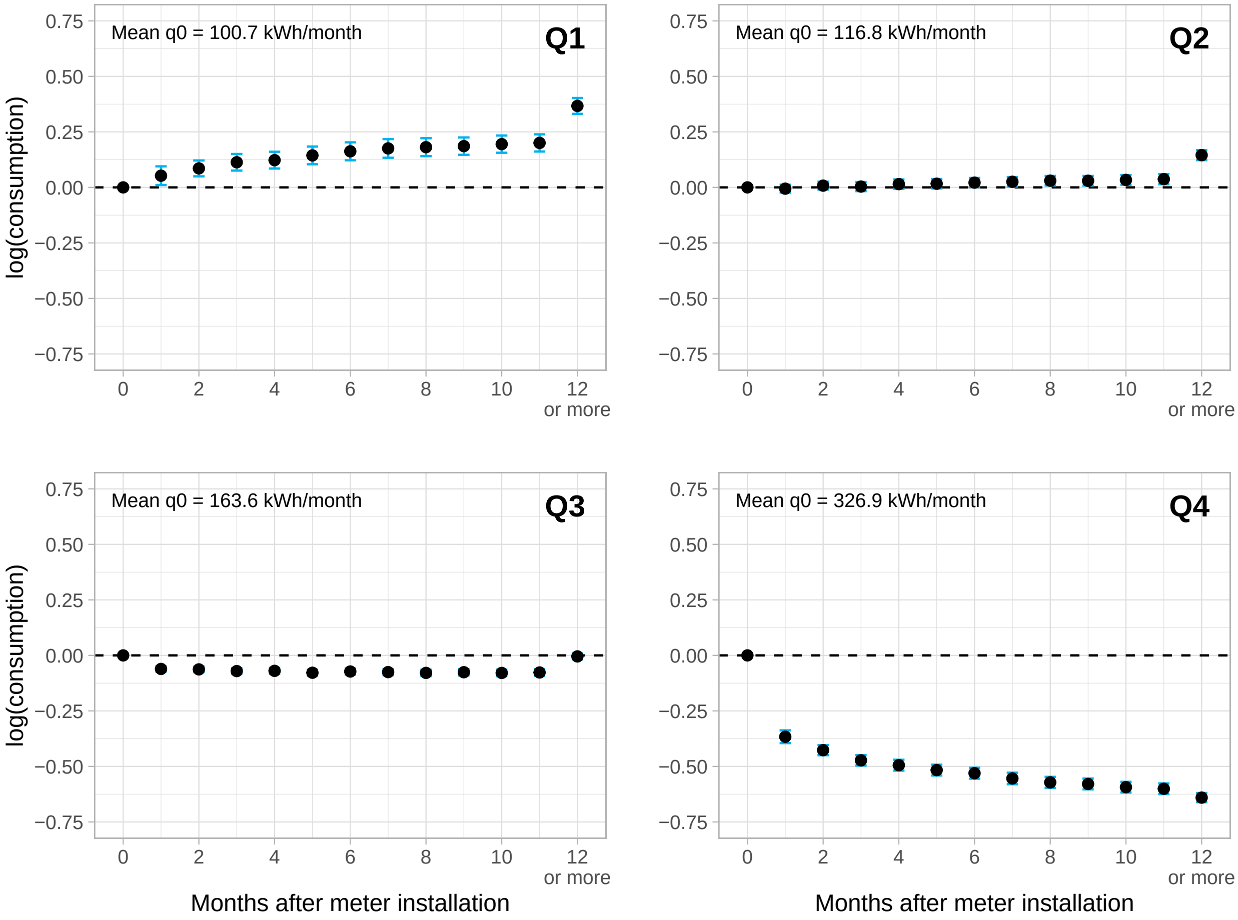
In this equation, q_{it} is the metered electricity consumption of household i in month-of-sample t. The β_k are coefficients on indicator variables for the number of months since meter installation, where the first month is the excluded group and all months after one year are grouped in the final category. The α_i are household fixed effects, and the γ_{rt} are distribution network territory by month-of-sample fixed effects.

The advantage of using a linear model in the previous section (Equation (1)) was that the linearity enabled me to examine overall changes in billed consumption in the switch from unmetered to metering consumption, despite the model being at a household level. In contrast, I estimate Equation (3) using log consumption as the dependent variable to interpret the coefficients as percentage changes in consumption relative to the first-metered-consumption baseline.

The other modeling change compared to the previous section is the definition of the control group. The never-metered households do not provide useful controls for changes in household consumption once they are metered. Instead, I define the control group for each quartile as all always-metered households at the same transformers as the newly-metered households. All observations in the regression are the consumption of metered households (either newly-metered or always-metered).

In each case, the base period for the newly metered households is the first metered month after meter installation. Because households have not received information about

Figure 7: Post-metering change in electricity consumption by quartile of initial relative consumption



their true electricity consumption and how it will be used to calculate their new bills, this period provides the best available measure of the household's consumption in the absence of metering. This interpretation is consistent with the results in Figure 4, showing relatively little change, on average, between the last unmetered billed consumption and the first metered consumption.

Figure 7 shows the results for estimating Equation (3) for each quartile. Quartile 1 comprises those households who would have received the largest reduction in their electricity bill after meter installation. Remarkably, the mean electricity consumption of households in this quartile increased relative to their baseline period. From a mean baseline of 100 kWh per month, consumption increased by about 22 percent during the first year after meter installation. The long-term effect was even larger: about a 44 percent increase.

The opposite result is seen for Quartile 4, the households that would have received the largest increase in their electricity bill after meter installation. These households sharply reduced their electricity consumption by 31 percent in the month after receiving their first metered bill. They continued to reduce consumption over the following 12 months, with their overall consumption dropping by 47 percent compared to their pre-metered quantities.

The middle two quartiles represent those households with electricity consumption closer to the average for their local neighborhood. Electricity metering is relatively benign for these households: their first metered bill would have been similar in magnitude to their last unmetered bill. For households in these quartiles, the post-metering changes in their consumption are relatively small: about a 3.8 percent increase in consumption for Quartile 2 and a 7.4 percent decrease for Quartile 3.

5.2 Average versus marginal price response

One behavioral explanation for the results in Figure 7 is that they show households responding to average price (perhaps with a lag) rather than marginal price. The Quartile 1 households receive a large drop in their electricity bills after metering, implying that their perceived average price based on their true electricity consumption also falls substantially. In other words, Quartile 1 households increase their electricity consumption because their average price has fallen, even though their marginal price is higher.

The reduction in consumption for Quartile 4 households is consistent with both an average price and a marginal price response. For Quartile 4, both average and marginal prices increase substantially due to metering.

I use a regression framework similar to Ito (2014) to formally test the models of marginal and average price response. Specifically, I focus on the subsample of newly metered households for the first two years after the meter installation. For these households, I estimate the log-linear demand model in equation (4).

$$\log(q_{it}) = \beta P_{it-1} + \alpha_i + \gamma_{rt} + \varepsilon_{it} \tag{4}$$

In this regression, the dependent variable is the log of the metered quantity of household i in period t. The main regressor of interest is the lagged price term P_{it-1}. In different specifications, I use the marginal price, the average price, or both prices combined in a single regression. The regression also includes household fixed effects α_i and distribution-region-by-month-of-sample fixed effects γ_{rt}.

Because of the two-tier increasing block price schedule, the marginal price depends on the household's electricity consumption. Unmetered households are assumed to face a zero marginal price. Therefore, the lagged marginal price in the first month after the meter installation is zero. The average price is defined as the total billed consumption in pesos divided by the actual consumption in kilowatt-hours. In this case, the lagged average price in the first month after the meter installation is calculated from the last unmetered bill, divided by the initial metered quantity.

An empirical challenge for both the marginal and average price regressions is that the price and quantity are determined simultaneously. I construct instruments for both prices in all periods from the observed tariff schedule in each period, combined with the initial metered quantity for each household. Because these simulated instruments incorporate the actual tariff schedules in each period, they are highly correlated with the realized prices. Moreover, because the instruments do not incorporate the contemporaneous quantity in each period, they avoid the simultaneity problem that creates a correlation with the error term in the consumption regression.

The three columns in Table 1 show the results from instrumental variables estimation of Equation (4) for marginal price, average price, and both. Reassuringly, price has a negative effect on electricity consumption in all three models. The implied price elasticity of demand for the marginal price model (Column 1) is -0.27, consistent with many previous studies of electricity demand in low- and middle-income countries. For the model containing both marginal and average prices (Column 3), the coefficients on both prices are negative and statistically significant. This result is consistent with heterogeneity across consumers in their behavioral responses to being metered: some respond to marginal, and others respond to the average price.

5.3 Consumer surplus effects of metering

In the final component of the analysis, I use the demand estimation results with marginal price (Column 1 of Table 1) to calculate the change in consumer surplus from metering. The consumer surplus before metering is defined as the usual area under the demand curve above a marginal price of zero, less the fixed amount billed to the household based on the mean consumption of the other unmetered households at the same transformer. The consumer surplus after metering is defined as the area under the demand curve above the marginal price faced by the household on the increasing block tariff schedule plus the

Table 1: Demand for electricity based on marginal and average price

	(1)	(2)	(3)
Lagged marginal price (00 pesos/kWh)	-0.093***		-0.136***
	(0.007)		(0.020)
Lagged average price (00 pesos/kWh)		-0.144***	-0.037***
		(0.033)	(0.014)
Fixed effects			
Household (93,237)	Y	Y	Y
Market-Month-of-sample (2,418)	Y	Y	Y
Observations	1,980,623	1,980,623	1,980,623

Notes: The observations in all regressions are the monthly metered electricity consumption for newly metered households in the first two years after metering. Prices in the three regressions are instrumented using a simulated instrument constructed from the contemporaneous tariff schedule and the initial quantity. Standard errors in parentheses are clustered by municipality.

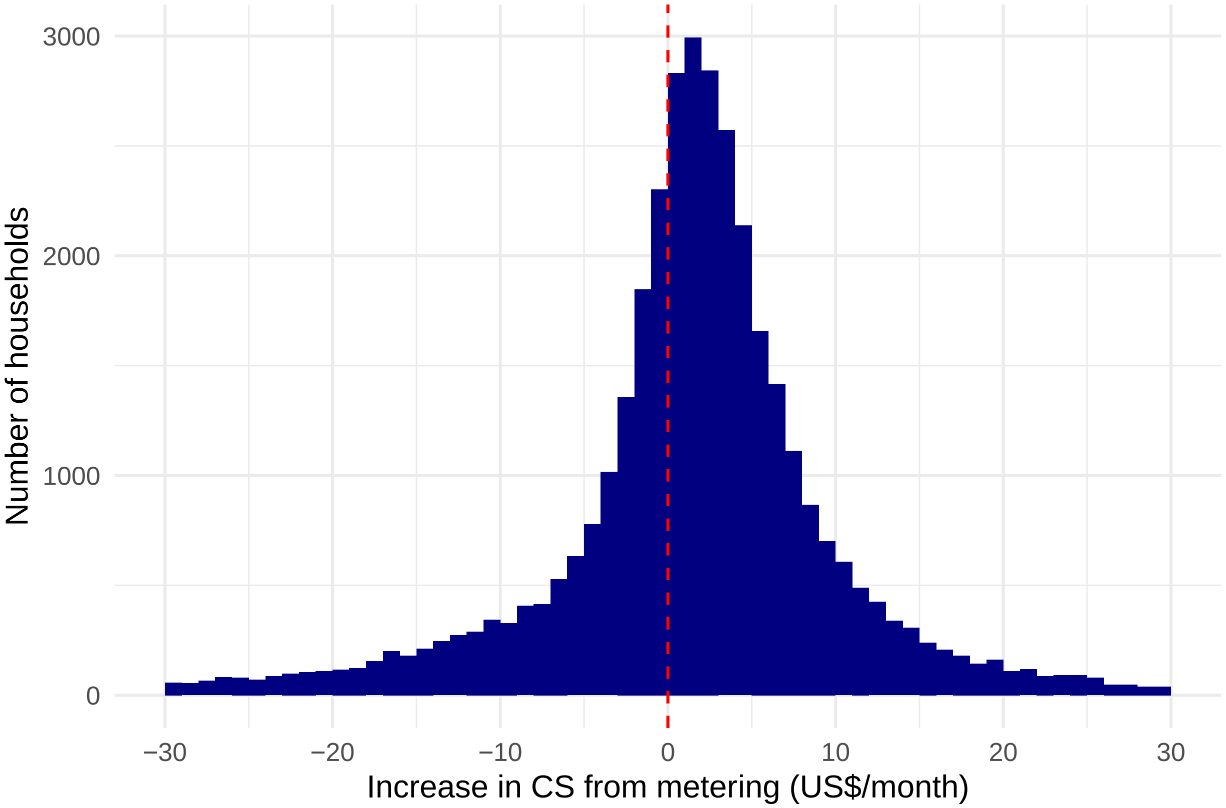
value of any inframarginal subsidies for households on the higher tier of the schedule.

Specifically, I use the demand model to predict the unmetered consumption of each household when the lagged marginal price is zero. I calculate the mean of the unmetered quantity by transformer and then use the actual tariff schedule to calculate the fixed amount billed to each household before metering. I then use the demand model to predict the metered consumption of each household during the two years after metering, given that the household faces the true marginal price on the tariff schedule. These two years of metered consumption are averaged to give a simple before and after comparison of the consumer surplus effects of metering.

Figure 8 shows the change in consumer surplus (in US$ per household-month) from metering for the households at transformers that previously had five or more unmetered households. Most households are better off as a result of metering. The median gain in consumer surplus is US$1.71 per household-month, and the mean is US$0.77 per household-month. In general, the households that benefit most from metering are those with lower levels of consumption who were being billed for the higher average quantity of their neighbors. The model predicted unmetered consumption of the households who are better off after metering was 115 kWh/month. The households worse off after metering had a predicted unmetered consumption of 246 kWh/month.

Note that metering creates more than a zero-sum transfer between households with high and low consumption. The mean consumer surplus is greater after metering. This is because, as illustrated in Section 2, metering eliminates the excess consumption at a

Figure 8: Distribution of the change in consumer surplus from electricity metering



marginal price of zero for which the marginal benefit is low.

6 Conclusion

The transition from fixed to volumetric charges has been an important step in the historical evolution of public utility services. Individual metering enables both the efficient pricing of utility services and the allocation of costs across users based on usage. In this paper, I quantified the efficiency and distributional effects of transitioning nearly 100,000 previously unmetered households in Colombia to individual electricity meters. There are three key findings. First, mean billed consumption falls by more than 25 percent after metering, partly due to behavioral changes from households facing non-zero marginal prices for the first time. Second, there is substantial heterogeneity in the household-level effects, with the lowest-consumption households increasing their usage after metering and the highest-consumption households decreasing their usage. Finally, most households are better off after metering, with the lowest-consumption households experiencing the greatest gains in consumer surplus.

The adoption of real-time electricity pricing provides an interesting parallel to my setting in Colombia. In many countries, there has been a widespread rollout of real-time meters to measure consumption on a fine temporal scale. However, the granular information is rarely used for calculating electricity bills, which are usually still based on total monthly consumption. This implies that consumption is inefficiently high during hours when the marginal price of electricity is high. Moreover, there is a transfer from households with low consumption during high-price hours to households with high consumption (Leslie et al., 2023), in the same way that I showed a transfer from households with low unmetered consumption to households with high unmetered consumption. Eliminating these temporal cross-subsidies is a rarely considered benefit of real-time pricing. In other words, the efficiency and distributional effects of "unmetered" electricity consumption are present in public utility tariffs that do not use real-time prices.

An ongoing challenge for designing electricity tariffs is the increasing share of fixed costs in the total cost of providing electricity service. This is caused by the greater use of distributed solar generation reducing the quantity of electricity purchased, as well as lower wholesale electricity prices due to low-marginal-cost generation from renewable sources. Using average-cost tariffs creates a larger gap between the marginal price for consumers and the marginal cost of production. This gap provides a disincentive to consume electricity—a problematic result given that "electrifying everything" is a popular proposed pathway for eliminating fossil fuel consumption.

An alternative electricity tariff combines a high fixed charge with low time-varying prices for usage. However, this tariff design would bring utilities full circle to the distributional concerns from charging similar amounts to high and low users. Resolving this problem requires varying the fixed charge across consumers, perhaps based on their income or their estimated willingness to pay. However, designing a varying fixed charge creates new challenges of data requirements, administrative complexity, and political feasibility. The information collected by real-time electricity meters may be an important input for solving these challenges. The ongoing interaction between tariff design and metering technology will be essential for balancing the efficiency and equity trade-offs of the clean energy transition.

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