Electricity Pricing for the Energy Transition*

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Abstract

High electricity prices in the commercial and industrial sectors hinder efforts to decarbonize through electrification. In this paper, we demonstrate the inefficiencies of the retail electricity tariffs for both non-residential and residential consumers in Colombia. We propose a novel tariff design that eliminates customer class distinctions, aligns prices with marginal costs, and introduces a fixed charge based on estimated willingness to pay. Using data for the entire population of electricity consumers in Colombia, we illustrate the tariff's potential to eliminate existing distortions in electricity pricing across customer classes while limiting bill increases for low-income households.

JEL: L53, L94, O25, Q41

Keywords: electricity tariffs, price distortions, fixed charges, Colombia

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1 Introduction

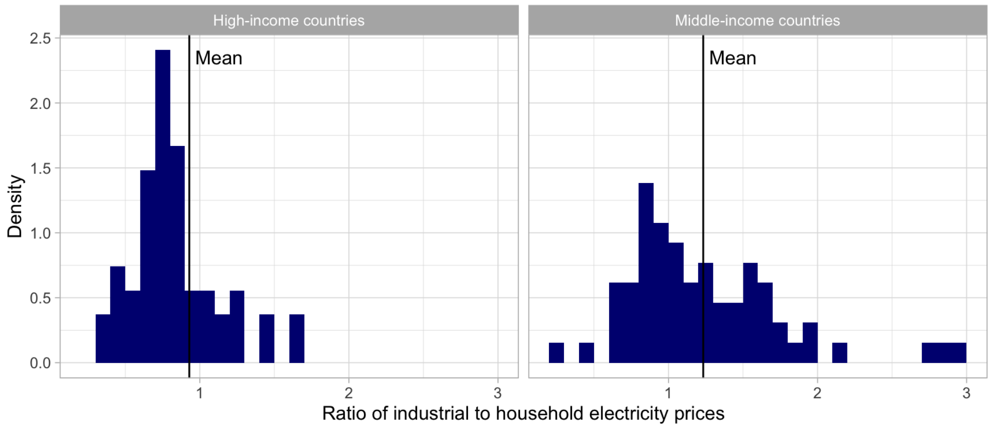
Electricity consumption by commercial and industrial customers comprises more than 60 percent of global electricity use. Under current policies, electricity demand in these sectors will grow by about 2 percent annually over the coming decade, with even higher growth expected under more aggressive climate change policies (IEA, 2022). These high growth rates reflect the essential role of electrification in achieving decarbonization objectives. For example, new technologies will allow electricity to replace fossil fuels in many high-emissions industrial processes. In the commercial sector, electricity can replace fossil fuels for space heating, water heating, and cooking.

In most middle-income countries, the existing electricity tariffs for commercial and industrial customers are unsuitable to encourage the transition to a low-carbon economy. Many countries have non-residential electricity prices that are higher than residential prices and substantially higher than the marginal cost of electricity generation. For example, in Mexico, commercial and industrial customers pay an electricity price between two and three times higher than the price paid by most households. This situation is not uncommon. The mean ratio of non-residential to residential electricity prices is about 1.2 in middle-income countries, compared to a mean below 1.0 in high-income countries (Figure 1). These high prices reflect the use of implicit or explicit cross-subsidies from the non-residential sector to the residential sector, as well as the use of average cost pricing for recovering the fixed costs of electricity supply.

The higher average electricity prices for commercial and industrial customers relative to residential customers are not justified by cost differences. Commercial and industrial customers typically connect to distribution networks at higher voltage levels, which implies lower distribution grid access charges relative to residential consumers. Most commercial and industrial customers have hourly load shapes that imply an average cost of wholesale energy lower than the typical residential hourly load shape. Commercial and industrial customers are also more likely to have modern meters that can record their hourly electricity consumption, which implies that they have both the ability and incentive, given their substantially larger monthly electricity bills, to change their consumption in response to hourly wholesale prices. For these reasons, in all major industrialized countries, commercial and industrial customers typically pay significantly lower average prices for electricity than residential customers.

This paper studies the distortions in the existing tariff structure for non-residential and residential electricity consumers in Colombia. These tariffs have no fixed charges

Figure 1: Distribution of the Ratio Between Industrial and Residential Electricity Prices, by Country Income Classification



Notes: Each histogram shows the distribution of the ratio between industrial and residential electricity prices by country. A value of 1 means that the industrial price is the same as the residential price. Prices as of 2019. Data obtained from https://www.globalpetrolprices.com/electricity_price.

and are based on average cost recovery. As a result of residential electricity subsidies, a substantial share of households pay a marginal price for electricity lower than the marginal cost of electricity supply. These households have an incentive to consume too much electricity. Conversely, because the base tariff is determined based on average cost pricing, all non-residential electricity consumers and many households face a marginal price much higher than the marginal cost of electricity supply. These customers have an incentive to consume less than the socially optimal quantity of electricity. Moreover, they face a strong disincentive to invest in electrification technologies and reduce their fossil fuel consumption.

We propose an alternative tariff that eliminates these distortions in the existing pricing structure. Under our alternative tariff, all electricity consumers, both residential and non-residential, face a time-varying hourly marginal price for their electricity consumption set equal to the marginal cost. While the revenue from the real-time tariff would be sufficient to cover the generation cost, it will not cover the retailing and distribution costs of electricity supply. Our proposed tariff provides a methodology for calculating a monthly fixed charge for each electricity consumer, proportional to their estimated expected hourly willingness-to-pay for electricity (Wolak, 2018). The total amount of these monthly fixed charges will equal the remaining fixed electricity supply costs that are not recovered through the hourly marginal price.

Two novel aspects of our proposed tariff make it particularly suitable to incentivize the energy transition. First, the tariff eliminates all existing customer categories. The amount each customer pays depends only on their hourly consumption profile, not on whether they are a household, hospital, or shop. Changing electricity generation and consumption patterns—for example, residential customers may now have on-site generation and storage—are making historical customer class distinctions increasingly irrelevant. Moreover, tariffs that vary based on the customer category create incentives for electricity users to engage in socially wasteful attempts to change their tariff classification. The second advantage of our tariff is that the bill depends only on information collected by the distribution utility about the hourly usage of each customer. It does not require utilities to have access to potentially sensitive financial information about their customers to use as a crude proxy for willingness to pay.

We illustrate the distributional implications of our proposed tariff using one year of detailed data on the electricity consumption and bills of every electricity consumer in Colombia—both residential and non-residential. Our sample comprises 160 million electricity bills from 12.7 million customers, of which approximately 90 percent are residential. Moreover, our data come from thirty separate distribution utilities, each with a different base tariff level and a varying composition of customer types. We combine this billing data with hourly metered data for nearly 2,000 large, unregulated electricity consumers (almost all commercial and industrial users) free to choose their electricity retailer and negotiate their tariffs. Along with hourly data on the withdrawals from the transmission network for each electricity distributor, we use this data to estimate each customer's hourly profile of usage and their wholesale electricity supply cost.

With our comprehensive data on the universe of electricity consumers in Colombia, we calculate our proposed alternative tariff for each distribution network and electricity customer. We then compare customer payments under the existing tariffs to the amount each customer would pay under the proposed tariff. Non-residential customers in the bottom 80 percent of the consumption distribution would be better off under the proposed tariff. These customers are paying the highest price with the existing tariff. Large non-residential customers would face a substantial increase in their electricity bills. The pattern is reversed for residential consumers: on average, residential customers in the bottom 80 percent of the consumption distribution would be worse off under the proposed tariff. However, their electricity bill increase would be relatively small, with the average bill increasing by only about US$1.50 per month. Residential customers with high consumption would see a reduction in their bills.

Overall, our results show that it is feasible to change the existing tariff structure to provide correct incentives for consuming electricity and investing in electrification. Given the existing subsidies provided to residential electricity consumers, it is not possible to design an efficient tariff that would make every user better off compared to the status quo. Nonetheless, our methodology for varying the fixed charge across customers ensures that the bill increase for households with low consumption will be relatively small.

This paper contributes to a small amount of recent literature on designing economically efficient electricity tariffs to support the energy transition. Burger et al. (2020) compare alternative tariff designs for residential electricity consumers in Chicago, focusing on two-part tariffs with a real-time price equal to marginal cost. They consider three methods to vary fixed charges to reduce the effect of a uniform fixed charge on low-income households: historical consumption, customer income, or geographical information. Borenstein et al. (2022) use residential billing data from the three major utilities in California to show the inefficiencies of the existing tariff structure and then discuss alternative methodologies for residual cost recovery, including setting a fixed charge based on household income. McRae and Wolak (2021) use household survey data from Colombia to illustrate the inefficiencies of the existing tariffs and then demonstrate the distributional effect of an efficient two-part tariff with a fixed charge that varies based on the estimated willingness-to-pay.

The significant contribution of this paper compared to this previous literature is that we demonstrate how an economically efficient tariff can be designed and used for all electricity consumers rather than restricting the analysis to residential customers. As discussed above, in many countries, there are significant distortions in electricity pricing across different customer classes, not just within one particular category of consumers. Alternative tariff designs that vary the fixed charge based on household income, for example, have no obvious extension to the non-residential sector.

The remainder of this paper is organized as follows. Section 2 provides background information on electricity tariffs in Colombia. Section 3 provides the theoretical basis for our alternative tariff proposal. Section 4 describes the data used to illustrate the alternative tariff, and Section 5 shows our empirical methodology. The results for the alternative tariff are shown in Section 6. Section 7 concludes.

2 Background

Electricity users in Colombia are served by 30 distribution utilities, each a monopoly within its service territory.[1] Since 1994, electricity tariffs in Colombia have been regulated by the Energy and Gas Regulatory Commission (CREG). CREG sets a formula for each component of the base tariff that distribution utilities can charge. Most of these tariff components are set using an average cost methodology so that the utilities can recover their costs and earn a regulated rate of return on their invested capital.

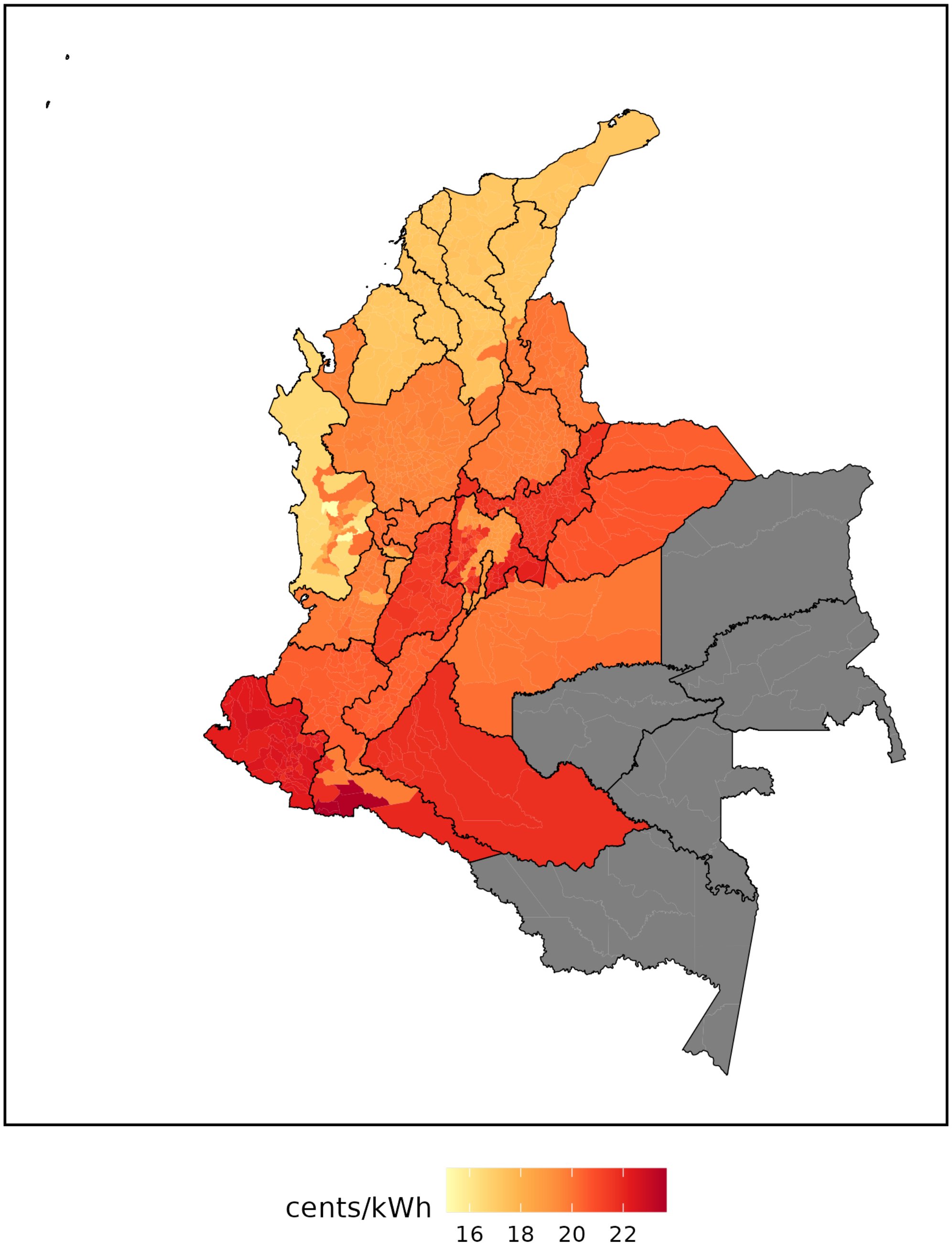
There is substantial variation across Colombia in the regulated base tariffs (Figure 2). Among the major utilities, the lowest tariffs in 2014 were on the Caribbean coast, in the former service territory of the (now liquidated) Electricaribe. The highest tariffs were in the southern departments of Nariño and Putumayo, followed by the departments in the eastern lowlands. Because the wholesale electricity price is the same everywhere in Colombia, there is little variation in the generation component of the base tariff, with only small differences due to forward contract pricing and timing. Instead, most of the tariff differences are the result of the distribution and retailing components. Because these costs are mostly fixed, the largest utilities such as Electricaribe, EPM, and Codensa can divide them by a greater number of kilowatt-hours sold, reducing the average cost per kilowatt-hour. These components are greatest for smaller and more rural distribution utilities.

Few electricity users in Colombia pay the base tariff. Instead, there is a system of cross-subsidies designed to reduce the price paid by households in lower-income neighborhoods. These subsidies are financed, in part, by households in higher-income neighborhoods and commercial and industrial electricity users. Specifically, each residential customer is assigned to one of six strata (*estratos* in Spanish), with the assignment carried out by the local municipal authority based primarily on the external characteristics of each neighborhood. Most households in Colombia are assigned to Strata 1, 2, or 3, and receive a subsidy of approximately 55 percent, 45 percent, or 15 percent for their first block of electricity consumption each month.[2] Above the subsidized amount, households pay the regulated base tariff. The price schedule is an increasing block tariff, meaning that subsidized households with high consumption still keep the subsidy on their inframarginal

1. There has been substantial consolidation among the distribution utilities. The largest utility, *Empresas Públicas de Medellín*, has acquired many smaller utilities in several different regions of Colombia. In most cases, these acquired utilities have retained the brand identity and are still regulated independently.

2. The size of the subsidized block varies by altitude. Households in warmer regions, defined as municipalities below 1,000 meters above sea level, receive the subsidy for their first 173 kWh each month. Households in cold regions, above 1,000 meters, receive the subsidy for their first 130 kWh each month.

Figure 2: Regulated Base Electricity Tariffs in Colombia in 2014



Notes: The map shows the mean regulated base tariff in each municipality for 2014, assumed to be the tariff for a low-voltage non-residential user with connection equipment owned by the distribution utility, excluding any contribution. Tariffs are converted from Colombian pesos to US dollars using the mean exchange rate for each billing cycle. Municipalities with missing data are filled in from the department average. Grey departments are not connected to the national transmission network.

consumption. Households in Stratum 4 pay the regulated base tariff for their entire consumption.

Households in Strata 5 and 6, as well as commercial and industrial customers, pay a 20 percent ad valorem tax on the regulated base tariff. This tax is used to fund the subsidies for the Strata 1 to 3 households. Each month, the electric utilities calculate the total subsidies paid out and the total contributions received. The Colombian government pays any shortfall, or receives any surplus, through a central redistribution fund known as the FSSRI (for its initials in Spanish). The overall fund runs at a deficit, which is funded by the government out of general taxation.

An important change to the system of subsidies and contributions occurred as part of a broader package of fiscal reforms in 2010 (Ley 1430 de 2010). This law eliminated the 20 percent contribution from industrial users as of 2012. The exempted sectors were defined based on their industrial classification code and included agriculture, forestry, mining, manufacturing, maintenance services, water and electric utilities, construction, and publishing. However, exemption from the tax was not automatic, and less than 20 percent of industrial customers applied for and received the exemption. As a result, most non-residential customers continue to pay the 20 percent contribution.

Not all electricity users in Colombia pay the regulated tariffs. Large electricity consumers, defined as those with demand exceeding 100 kW or a monthly consumption exceeding 55,000 kWh, can choose to contract directly with an electricity retailer and pay a mutually agreed tariff. Unlike in the regulated market, where users must receive retail service from their local utility, there is retail competition in the deregulated market. Although their electricity price is not regulated, all deregulated users are still required to pay the 20 percent tax on their consumption, unless they receive the exemption.

3 Theory for Alternative Tariff Structure

In this section, we describe a new electricity tariff design that eliminates the current tariff differences between customer classes and provides all electricity consumers with socially efficient incentives to consume electricity.

A bedrock principle for an efficient electricity tariff design is that all customers pay a time-varying marginal price set equal to the social marginal cost each hour at the customers' location. This price varies hour-by-hour based on the wholesale price for electricity. If electricity generators are taxed based on the social cost of their local air pollution and greenhouse gas emissions, with these taxes then incorporated into the offer prices submitted to the market operator, then the wholesale price will reflect the hourly social marginal cost of electricity generation including the environmental externalities. Ideally, the electricity price will vary across locations to reflect real-time constraints in the electricity transmission network as well as transmission line losses. Such a system of locational marginal prices is not currently used in Colombia but is found in all wholesale electricity markets in the United States.

Marginal cost pricing for electricity does not provide sufficient revenue to recover all costs associated with electricity supply. In particular, marginal cost pricing based on the wholesale electricity price will recover the generation cost, but not the cost of distribution and retailing. Under the current tariff system, distribution and retailing costs are recovered using an average cost price—but this distorts the incentives for electricity consumption.

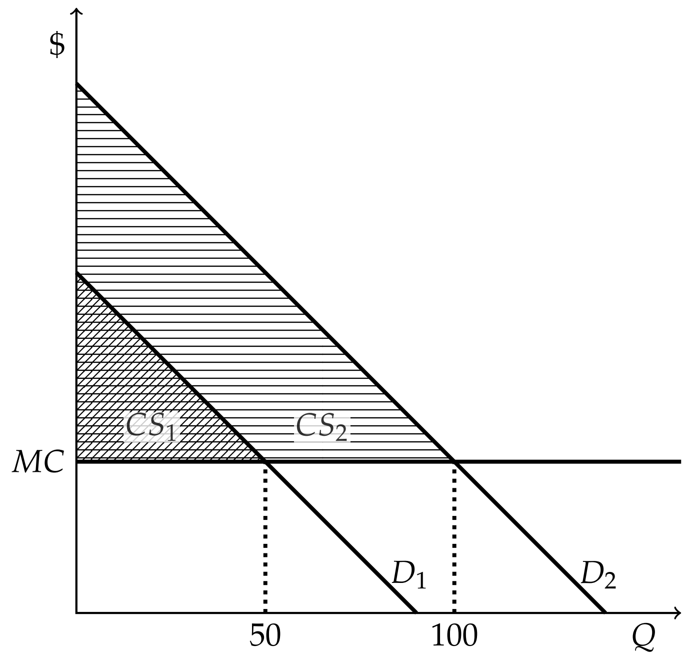
In our alternative tariff proposal, all remaining costs of electricity supply will be recovered through fixed monthly charges. We envisage two components of the fixed charge. The first component is the same for all electricity customers within a particular voltage level. In particular, the charge will be the same for all residential and non-residential customers with a standard low-voltage connection. In our empirical illustration below, we set the low-voltage charge as US$1 per month.

The second (and more novel) component of the fixed charge is based on an allocation of the remaining revenue requirement in proportion to the estimated expected hourly willingness to pay (EEHWTP) for each electricity consumer, both residential and non-residential. Electricity distribution utilities with access to the hourly metered electricity consumption of each customer throughout the year will be able to use this information alone to estimate the EEHWTP, updating the fixed charge paid by each customer on an annual basis. Further theoretical discussion of the EEHWTP mechanism is provided by Wolak (2018) and McRae and Wolak (2021).

Figure 3 provides a simple stylized example to motivate the rationale for and calculation of the EEHWTP. Suppose the electricity demand of a customer varies each hour with, say, 50 percent of hours with demand D_1 and 50 percent of hours with demand D_2. For the hours with demand D_1, the consumption at the marginal cost price MC is 50, and the total willingness to pay for electricity is the area CS_1. For the hours with demand D_2, the consumption at MC is 100, and the total willingness to pay is the area CS_2.

Given the assumptions in this stylized example that (i) demand is linear, and (ii) demand curves are parallel (that is, the slope is the same), the area CS_2 is four times larger

Figure 3: Stylized Example of Expected Hourly Willingness to Pay



than the area CS_1. This is the case even though the quantity demanded in the hours with demand D_2 is only twice the quantity demanded in the hours with demand D_1. The expected consumption for this customer is 75. However, the expected hourly willingness to pay to proportional to the expected squared consumption. For this example, assuming a demand slope of 1, the expected willingness to pay will be $0.5 \times 0.5 \times 50^2 + 0.5 \times 0.5 \times 100^2 = 3125$.

We can provide an alternative expression for the EEHWTP using the standard formula for the variance in terms of the expected square and the squared expectation:

$$EEHWTP = E[Q_h^2] = (E[Q_h]^2) + \text{var}(Q_h) \tag{1}$$

With hourly metered data across the 8760 hours of the year, either of these two expressions can be calculated for every customer.

Under our proposal, each distribution utility will update the EEHWTP for each of its customers on an annual basis, using each customer's hourly consumption for the previous year. The utilities will then allocate their revenue requirement across their customers in proportion to the share of each customer's EEHWTP in the aggregate EEHWTP. As shown in Equation (1), customers with higher mean consumption, or with greater variance in their consumption, will have a higher EEHWTP and will be assigned a higher fixed charge.

4 Data and Descriptive Statistics

In the rest of the paper, we provide an empirical illustration of the tariff design proposed in Section 3. For every electricity customer in Colombia, we compare the current amount that they pay for electricity to the amount that they would pay under the alternative tariff. In this section, we describe the data used for this empirical exercise, along with a descriptive analysis of the existing distributions of electricity consumption, tariffs, and bills.

The primary data source for the analysis is the monthly billing data for all electricity consumers in Colombia during 2014. Supplementary data sources include (i) the hourly metered consumption for the largest electricity users during 2014, (ii) the hourly withdrawals from the transmission network for each of the electricity distributors during 2014, and (iii) the hourly wholesale market price. We focus on 2014 for the analysis because the hourly metered data is unavailable after 2016. Moreover, the Colombian electricity market faced multiple disruptions during 2015 and 2016 partly due to a decline in hydroelectric inflows, leading to unusually high wholesale market prices and the threat of rationing. As of 2023, the structure of retail electricity tariffs remains identical to 2014.

The variables in the billing dataset include the monthly billed consumption, the price paid per kilowatt-hour, the amount of any subsidies received or contributions paid, the amount of overdue charges from previous bills, and the bill total. The dataset also reports information on the connection type: the voltage level, whether the connection is aerial or underground, and the ownership of the connection assets. These variables all affect the tariff paid by each customer. The customer location is reported at a county (municipality) level, plus an indicator for whether the firm is in an urban area, rural area, or outlying village.

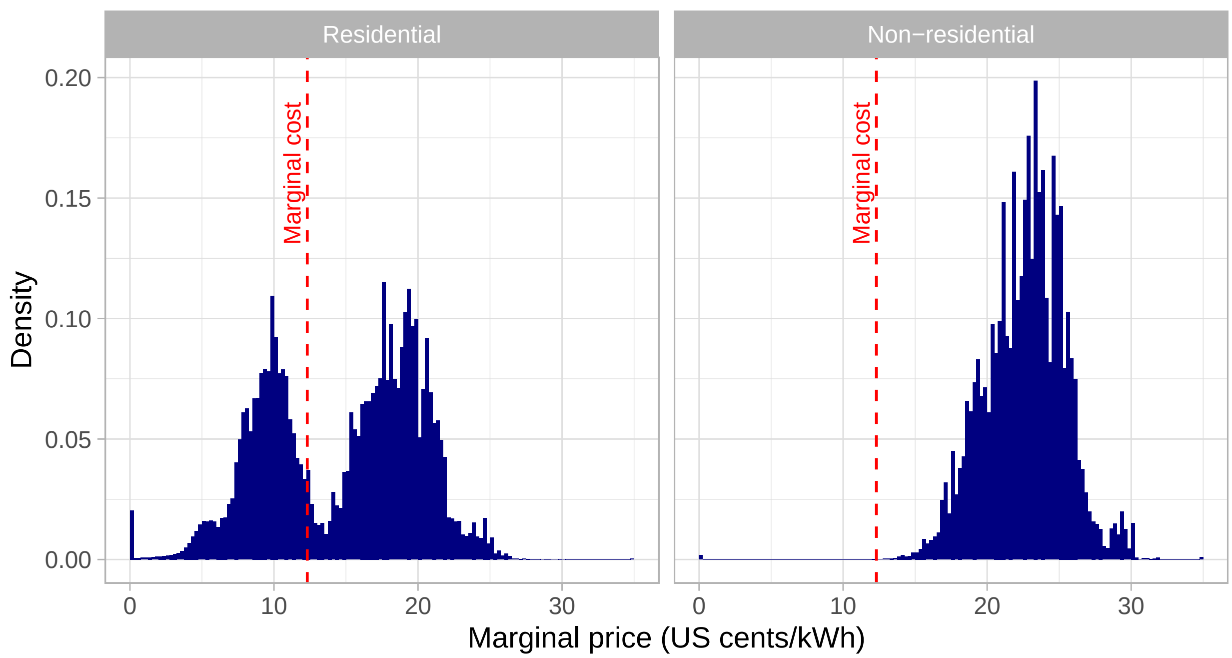
Table 1 provides summary statistics of the main variables in the billing data that are used in the analysis. There are 11.6 million residential customers served by the 30 electricity distributors. Each customer has an average of 12.6 bills with a billing period including at least one day during 2014, giving a total of 146.2 million bills in the data. Compared to residential customers, there are about one-tenth as many non-residential customers: 1.15 million. These customers also have an average of slightly more than 12 bills during 2014.

The mean consumption of residential electricity consumers is quite low: about 5 kWh per day, or 150 kWh during a typical 30-day billing cycle. The mean for non-residential

Table 1: Descriptive statistics

	P1	Mean	Median	SD	P99
Residential customers					
Consumption (kWh/day)	0.00	5.04	3.94	8.70	24.60
Marginal price (US cents/kWh)	3.94	14.73	16.07	279.51	24.60
Average price (US cents/kWh)	3.84	12.96	11.95	279.50	24.48
Total monthly bill (US$)	0.00	28.55	15.22	429.22	189.62
Share overdue (0/1)	0.00	0.12	0.00	0.33	1.00
Number of customers	11,577,512				
Number of bills	146,225,456				
Non-residential customers					
Consumption (kWh/day)	0.00	31.00	6.60	229.06	394.23
Marginal price (US cents/kWh)	16.18	22.68	22.88	31.98	29.46
Total monthly bill (US$)	0.00	271.77	51.85	11,053.02	3,036.31
Share overdue (0/1)	0.00	0.14	0.00	0.35	1.00
Number of customers	1,153,390				
Number of bills	14,029,610				

Figure 4: Distribution of Marginal Electricity Prices for Residential and Non-Residential Consumers during 2014



consumers is about six times higher (31 kWh per day). Moreover, the distribution of non-residential consumption is highly skewed. The 99th percentile of non-residential consumption is 394 kWh per day, more than 12 times greater than the mean consumption.

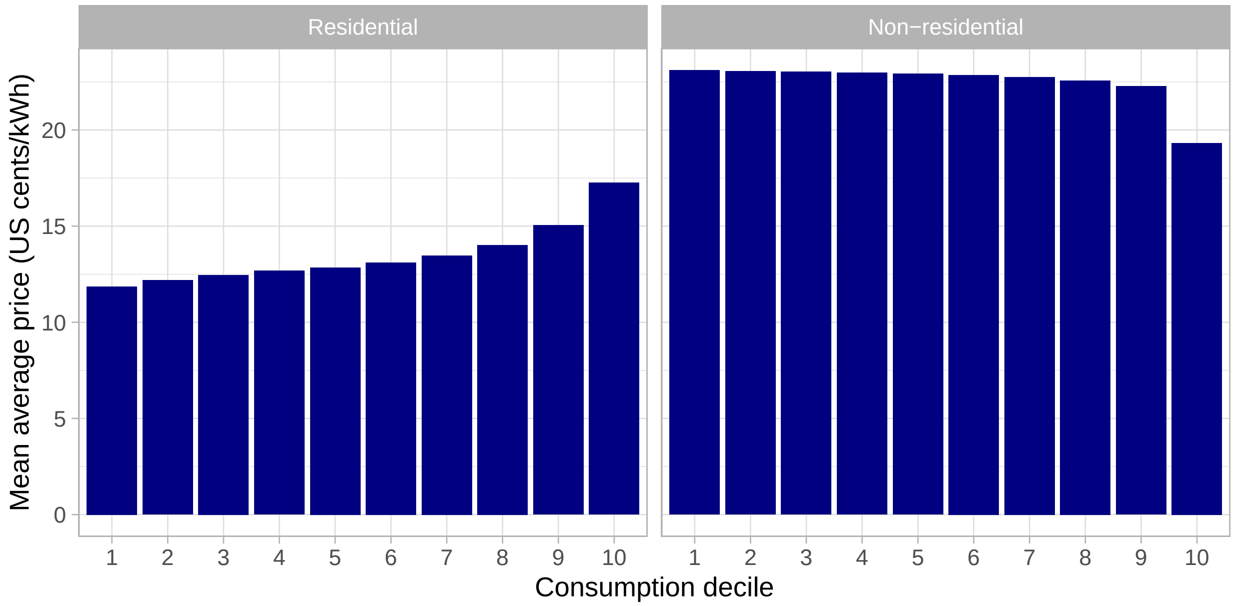
For each bill, the marginal price is defined as the amount by which the total bill would increase if consumption were 1 kWh higher. The average price is the total consumption component of the bill (inclusive of any taxes and subsidies) divided by the total consumption. The mean of the marginal prices faced by residential customers in 2014 was 14.73 US cents per kWh. This is higher than the average residential price (12.96 US cents per kWh) as a result of the increasing block tariff. With an increasing block tariff, the marginal price will always be greater than or equal to the average price for every bill.

Because all non-residential customers face a uniform tariff, the marginal price is equal to the average price for every bill and customer. The mean marginal price (also the mean average price) was 22.68 US cents per kWh during 2014, 75 percent higher than the mean average price for residential customers. The range of average prices in the non-residential sector is relatively small: from 16 to 29 US cents per kWh. By comparison, the average price range for residential customers is large: from 4 to 24 cents per kWh.

Figure 4 illustrates the distribution of marginal prices for residential and non-residential customers during 2014. The distribution for residential customers (left panel) is bimodal. The lower mode of about 10 cents/kWh corresponds to subsidized households on the first block of the tariff schedule, for whom the marginal price is the subsidized price. The upper mode of slightly less than 20 cents/kWh corresponds to the subsidized households on the second block of the tariff schedule paying the base tariff (shown in Figure 2). There is a smaller mass of households paying more than 20 cents/kWh, corresponding to customers in higher-income neighborhoods who contribute to the cross-subsidy scheme. Unlike the residential distribution, the distribution of marginal prices for non-residential customers (right panel) is unimodal, with a mode of about 24 cents/kWh. Most of these customers pay the base tariff in Figure 2 plus the 20 percent contribution.

The dashed vertical lines in Figure 4 show the mean hourly marginal cost of supplying electricity in Colombia during 2014. The marginal cost is calculated as the hourly wholesale market price, converted to US dollars using the daily exchange rate, scaled up by 1.08 to account for estimated transmission and distribution losses. Very few customers pay a marginal price close to the marginal cost of electricity supply. Most of the subsidized households on the first tier of the tariff schedule face a marginal price below the marginal cost. Non-residential customers and unsubsidized households, as well as subsidized

Figure 5: Average price by residential and non-residential consumption decile, based on existing tariffs in 2014



households on the second tier of the tariff schedule, face a marginal price far above the marginal cost. McRae and Wolak (2021) describe how this deviation from marginal cost pricing distorts both short-term and long-term electricity consumption decisions.

To illustrate the tariff differences across customers based on consumption level and customer class, Figure 5 shows the average prices for electricity in 2014. The left panel shows the average prices for residential consumers; the right panel for non-residential. Within each panel, the bars show the average price by the deciles of electricity consumption for that customer type. For the residential sector, consumers with the lowest consumption pay the lowest average price. This reflects the increasing block tariff used in most low to middle-income neighborhoods in Colombia. Because electricity consumption is positively correlated with income, customers with the lowest consumption are more likely to neighborhoods assigned the highest subsidy level, and their consumption stays within the initial subsidized block. For the nonresidential sector, the consumers with the lowest consumption pay the highest average price. Only non-residential customers with very high consumption are able to connect at high voltages and pay a lower average price.

An alternative approach for visualizing the distribution of electricity consumption and bills is to plot these as a Lorenz curve. Levinson and Silva (2022) first used this method to illustrate the variation in residential electricity tariff structures across electric utilities

Figure 6: Lorenz Curve for Electricity Consumption and Total Bills

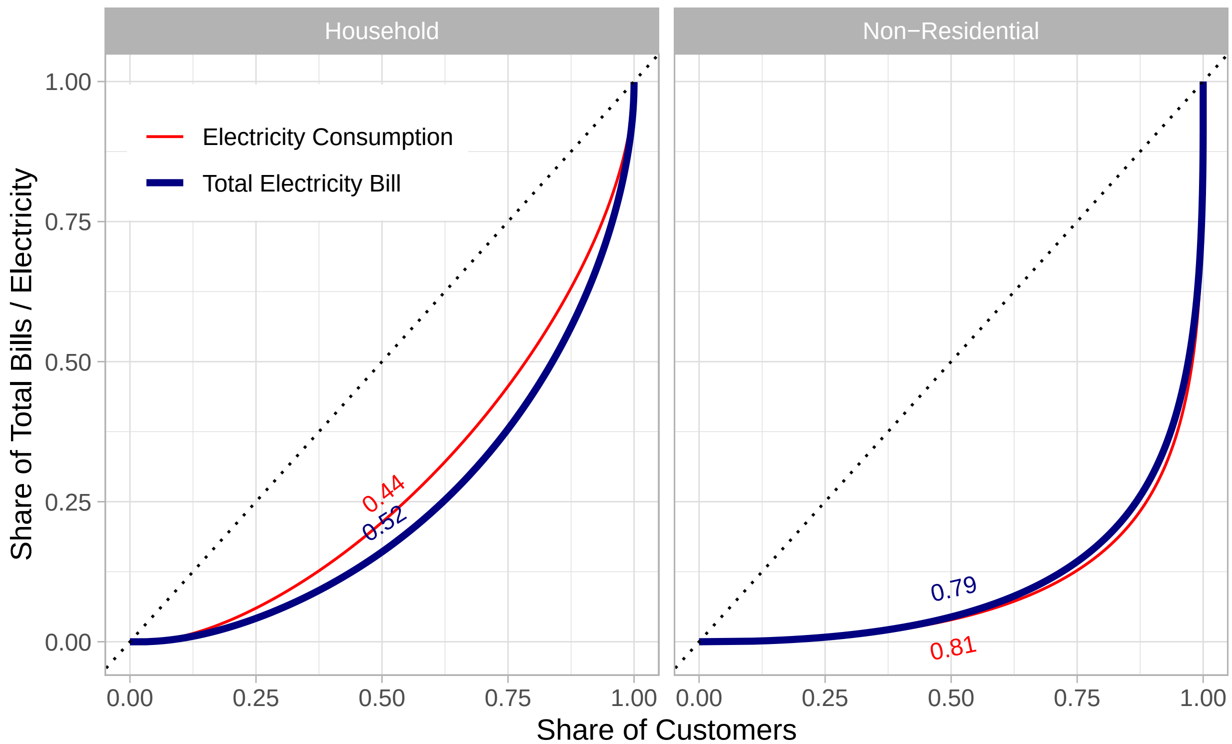
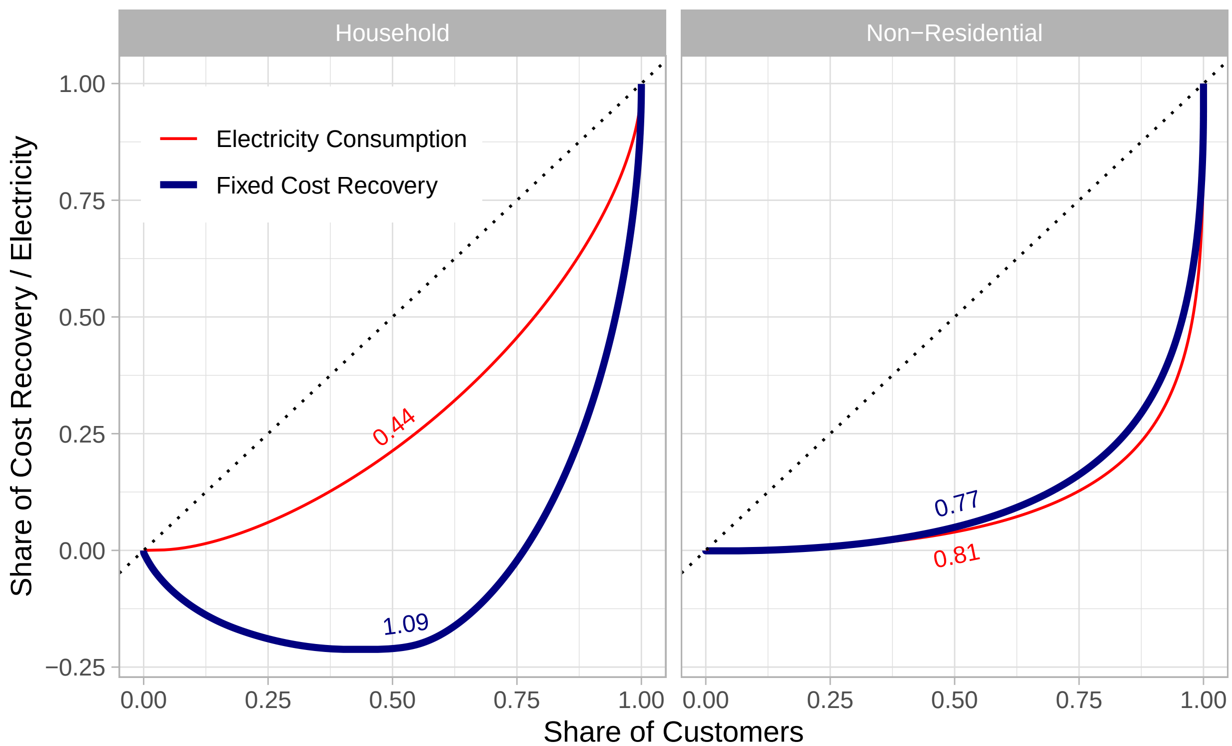


Figure 7: Lorenz Curve for Electricity Consumption and Total Cost Recovery



in the United States. Figure 6 shows the Lorenz curves for electricity consumption (thin red line) and total bills (thick blue line) for all residential and non-residential customers in Colombia during 2014. The Lorenz curve shows the cumulative percentage of total electricity consumption (or bills) on the vertical axis plotted against the cumulative percentage of the number of customers on the horizontal axis. If all customers had identical consumption, the Lorenz curve for electricity consumption would lie along the 45-degree line. The greater the curvature of the Lorenz curve, the more unequal the distribution of consumption. This curvature is summarized by the Gini coefficient shown alongside each curve. Higher values of the Gini coefficient correspond to a more unequal distribution.

As shown in Figure 6, the distribution of non-residential electricity consumption is considerably more unequal (Gini of 0.81) relative to the distribution of residential electricity consumption (Gini of 0.44). This is because most non-residential customers have low consumption similar to a typical household, but there are a small number of non-residential users with extremely high consumption. These high users comprise a large proportion of total non-residential consumption. The distribution of residential bills is more unequal than the distribution of residential consumption (Gini of 0.52 versus 0.44). This is a result of the subsidies received by many residential users that lower the total bill paid. Conversely, given the uniform tariff for non-residential users, the distribution of bills for these customers is similar to the distribution of consumption (Gini of 0.79 versus 0.81).

Figure 7 shows the same Lorenz curves for electricity consumption, with the addition of Lorenz curves for fixed cost recovery. The fixed cost recovered from each bill is calculated as the total billed consumption, less the estimated wholesale cost of the electricity consumption during the billing cycle (including estimated losses).[3] Remarkably, the Lorenz curve of fixed cost recovery for residential customers extends below zero and the Gini coefficient is greater than 1. This is because, as shown in Figure 4, slightly less than half of residential customers are paying a price below the marginal cost, so their bill payments do not even cover their variable costs of electricity supply. A small share of households pay most of the total fixed cost recovered from the residential sector. For non-residential users (right panel), the Lorenz curve for fixed cost recovery is always positive and is slightly less unequal than for electricity consumption (Gini of 0.77 versus 0.81). All non-residential users pay a price that exceeds marginal cost, but the largest users pay a lower price than the smallest users.

3. Additional details of the calculation of the fixed cost recovery are provided in Section 5.

5 Empirical Methodology

To illustrate our tariff proposal described in Section 3, we use the billing data for all electricity consumers in Colombia, described in Section 4. In this section, we provide the details of how we calculate the customer bills under the alternative tariff.

The first step in our empirical analysis is to impute the consumption in each hour of the year for every electricity customer. The largest nonresidential electricity consumers have interval meters and for these customers, we observe their hourly consumption directly. For non-residential consumers without interval meters, we allocate their monthly consumption across the hours of the month based on the load shape of nonresidential customers in the same sector (commercial, industrial, educational, healthcare, or public institutions). For example, we assume that a school without an hourly meter will have the same distribution of consumption across hours as a school with an hourly meter.

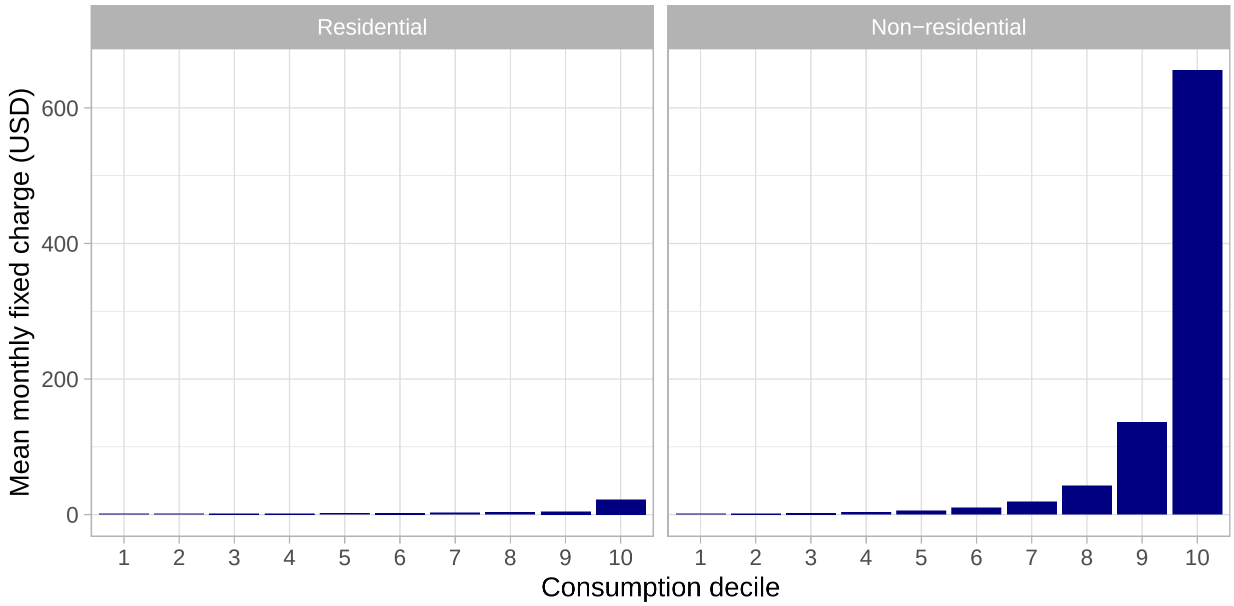
During the time period that we studied, few residential customers in Colombia had real-time electricity meters. We allocate the monthly consumption of each customer across the hours of each month based on the hourly aggregate load shape for the regulated customers served by each distribution utility. These load shapes show the expected daily pattern of consumption being higher during the early evening hours.

The next step in our calculation is to compute the total annual revenue requirement for each distribution utility. From the billing data, we calculate the total revenue collected from all customers, including the net subsidy contribution from the central government. We then use (i) the imputed hourly consumption of each consumer, with (ii) the hourly wholesale market price for each hour during 2014, to calculate the estimated wholesale cost of the electricity consumed during the year. The difference between the total revenue collected and the estimated wholesale cost is the revenue collected from the customer that contributed towards fixed cost recovery. Summing this difference across all customers for each utility gives the revenue requirement for each utility during 2014.

Using the imputed hourly consumption, we use the formulas in the previous section to calculate the EEHWTP for each customer during 2014. We aggregate the EEHWTP for all customers at the distribution utility level. Each customer is then assigned a fixed charge equal to its share of the total revenue requirement for the distribution utility, where the share is equal to the share of EEHWTP in aggregate EEHWTP.

For the results presented in the next section, we make two small modifications to the above procedure. First, we set an additional fixed charge that does not depend on EEHTWTP. This is set as $1 per month for low-voltage households and businesses, $10

Figure 8: Fixed Charges under Counterfactual Tariff Proposal, by Residential and Non-Residential Consumption Decile



per medium-voltage businesses, and $100 per month for the highest voltage connection. The revenue from this fixed charge reduces the total revenue requirement assigned by the EEHTWP mechanism. The second change that we make is to winsorize the customer-level EEHWTP values at the 99.5th percentile. This has the effect of reducing the fixed charge allocated to the customers with the highest mean and variance of hourly consumption.

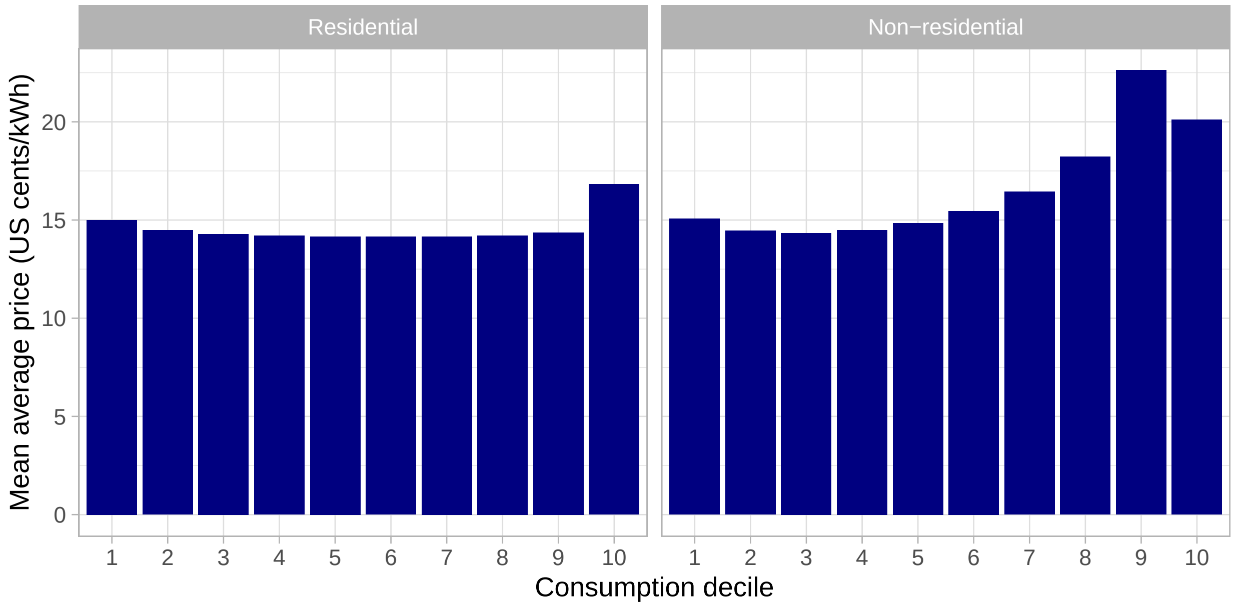
The proposed new tariff consists of marginal cost pricing based on the hourly wholesale cost of electricity (scaled up to account for transmission and distribution losses), plus a monthly fixed charge containing a voltage-dependent fixed charge and an additional revenue recovery component allocated in proportion to each customer's EEHWTP.

6 Results

Under our proposed tariff, all customers in Colombia will pay the same hourly price for electricity consumption. While these marginal prices are the same for everyone, the fixed charges will be very different (Figure 8). Except at the highest deciles, fixed charges are low for most households, and mostly comprise the US$1 charge set based on voltage levels. By far the highest fixed charges are imposed on the largest nonresidential customer.

The pattern of average prices (Figure 9) looks very different from average prices under

Figure 9: Average Price by Residential and Non-Residential Consumption Decile, under Counterfactual Tariff Proposal

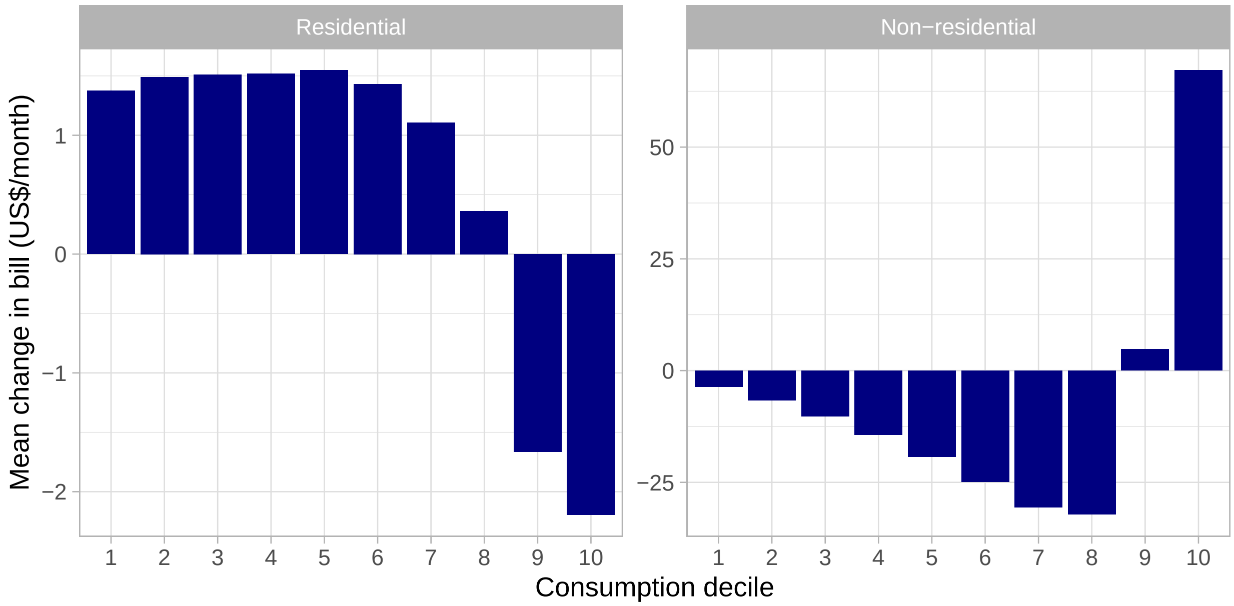


the existing tariffs (Figure 5. Average prices are similar for both residential and non-residential customers at the low end of the consumption distribution. The highest average prices are paid by the households and non-household customers with consumption in the 9th or 10th deciles. It is important to note that all customers, regardless of their consumption, face an identical marginal price. The only difference is in the cost recovery allocation based on the EEHWTP, which tends to be higher for customers with higher expected consumption.

To illustrate the distributional effects of the alternative tariff, Figure 10 shows the mean change by decile in the monthly electricity bill as the result of the switch from the status quo tariff to the proposed counterfactual tariff. Households with low consumption see an increase in their bills by slightly more than $1 per month. The households that benefit are those in deciles 9 and 10. The reduction in the marginal price they pay more than offsets the relatively high fixed monthly charge that they will be allocated.

Among the nonresidential customers (right panel of Figure 10), the first eight consumption deciles will benefit under the tariff proposal. They currently pay high average cost prices for their consumption. The switch to marginal cost pricing is favorable to them, even if they have to pay a new fixed charge. The only nonresidential customers that are worse off are the ones in the highest two deciles. The reduction in their marginal price is

Figure 10: Mean Change in Monthly Bills, Comparing Existing 2014 Bills to Bills under Counterfactual Tariff Proposal



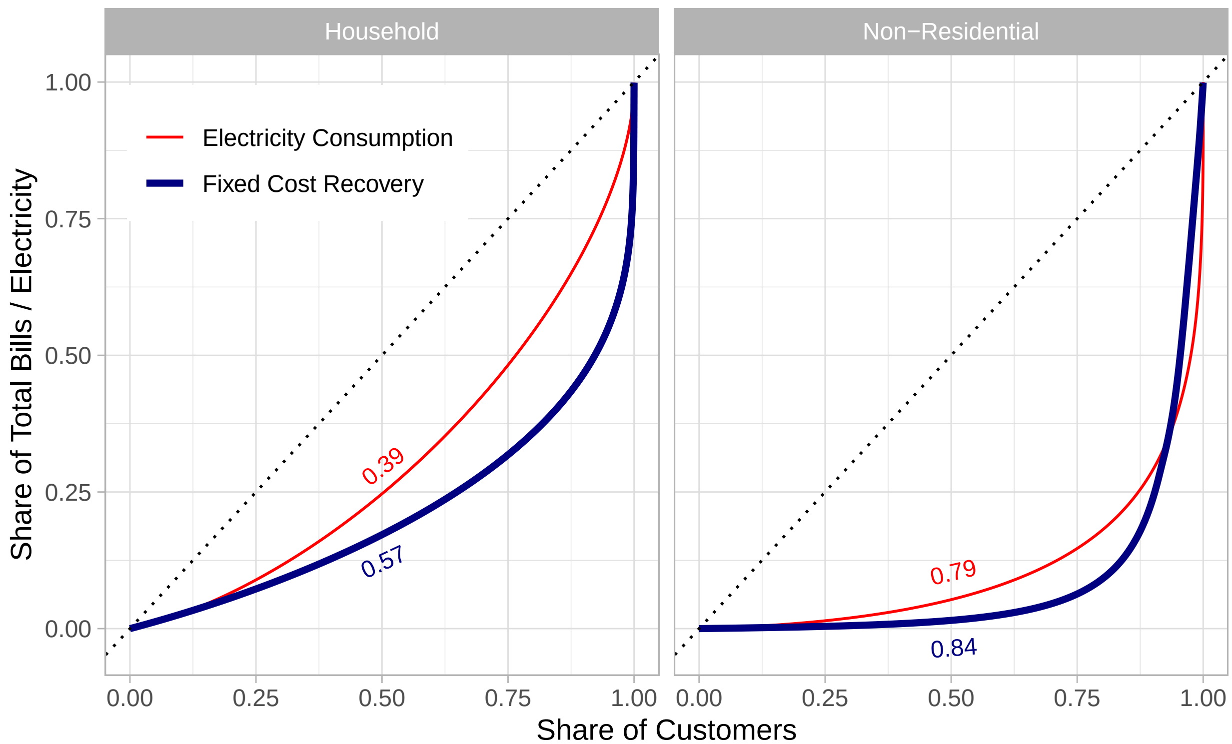
offset by the new high fixed charge allocation.

Finally, Figure 11 shows the Lorenz curves for total cost recovery under the tariff proposal. The most obvious difference from Figure 7 is that the residential Lorenz curve is always positive and the Gini coefficient (0.57) is less than 1. This is because all households pay a marginal price equal to the marginal cost of electricity supply, implying that the payment of every household covers its variable costs and makes a contribution (potentially very small) towards the fixed cost recovery. The second notable feature of the counterfactual Lorenz curves is that the distribution of fixed cost recovery is more unequal than the distribution of consumption, for both residential and non-residential users. In both sectors, larger electricity consumers (corresponding to those with a higher willingness to pay for electricity) pay a greater share of the fixed costs. This is not the case for non-residential customers under the existing tariff: smaller non-residential users make a more-than-proportional contribution to fixed cost recovery.

7 Conclusion

This paper proposes a transformation to electricity tariffs in Colombia that addresses fundamental inefficiencies in the current system. As in many jurisdictions around the world,

Figure 11: Counterfactual Lorenz Curve for Electricity Consumption and Total Cost Recovery Under Alternative Tariff Proposal



the current tariffs are remarkably unsuitable for providing incentives to encourage the transition away from fossil fuels. High-income households, households with high electricity consumption, and all non-residential customers face a marginal price for consumption that greatly exceeds the marginal cost of electricity supply. These tariffs discourage the electrification of energy services such as heating, cooking, and transportation.

Our proposed tariff aligns prices with the social marginal cost of electricity and introduces a customer-specific fixed charge based on estimated willingness to pay, offering a more equitable and efficient pricing structure. The basic principle of an economically efficient electricity tariff is well-known: all customers should face a time-varying hourly marginal price equal to the social marginal cost of electricity supply. The fundamental challenge is how to recover the residual costs. In this paper, we demonstrated a novel approach for residual cost recovery: a fixed charge that varies across customers in proportion to each customer's estimated expected hourly willingness to pay for electricity. An important feature of our approach is that it relies only on the hourly metered electricity consumption of each user. It does not require the utility to access potentially sensitive financial information as a proxy for willingness to pay. Moreover, our tariff eliminates all distinctions based on customer categories. Within each utility, every customer with the same hourly pattern of consumption will pay the same bill.

Our empirical illustration demonstrated that our alternative tariff will benefit most non-residential electricity consumers compared to the existing tariff while leaving the largest non-residential customers and the smallest residential customers worse off. The proposed increase in bills for low-income residential customers—in many cases, not much more than $1 per month—is small. Nonetheless, implementation of our tariff design would require careful consideration of these potential distributional effects, potentially ameliorating them through targeted government transfers to low-income households. Moving away from redistribution by way of electricity tariffs will be essential for achieving a transition away from fossil fuels at the lowest possible cost.

References

Borenstein, Severin, Meredith Fowlie, and James Sallee. 2022. *Paying for Electricity in California: How Residential Rate Design Impacts Equity and Electrification.* Technical report. Energy Institute WP 330.

Burger, Scott P, Christopher R Knittel, Ignacio J Pérez-Arriaga, Ian Schneider, and Frederik Vom Scheidt. 2020. "The efficiency and distributional effects of alternative residential electricity rate designs." *The Energy Journal* 41 (1): 199–240.

International Energy Agency. 2022. *World Energy Outlook 2022.* Technical report. https://www.iea.org/reports/world-energy-outlook-2022.

Levinson, Arik, and Emilson Silva. 2022. "The Electric Gini: Income Redistribution through Energy Prices." *American Economic Journal: Economic Policy* 14, no. 2 (May): 341–65. DOI: 10.1257/pol.20200543.

McRae, Shaun D, and Frank A Wolak. 2021. "Retail pricing in Colombia to support the efficient deployment of distributed generation and electric stoves." *Journal of Environmental Economics and Management* 110:102541.

Wolak, Frank A. 2018. *The evidence from California on the economic impact of inefficient distribution network pricing.* Technical report. National Bureau of Economic Research.