Journal of Environmental Economics and Management 110 (2021) 102541

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Retail pricing in Colombia to support the efficient deployment of distributed generation and electric stoves[☆]

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ARTICLE INFO

Keywords:
Energy transition
Tariff design
Rooftop solar
Cookstoves
Fixed charges
Distributional effects
Developing countries

ABSTRACT

Electricity tariff reform is an essential part of the clean energy transition. Existing tariffs encourage the over-adoption of residential solar systems and the under-adoption of electric alternatives to fossil fuels. However, an efficient tariff based on fixed charges and marginal cost pricing may harm low-income households. We propose an alternative methodology for setting fixed charges based on each household's willingness to pay to consume electricity at marginal cost. Using household-level data from Colombia, we demonstrate the short-run and long-run distortions from the existing tariffs and how our new methodology could provide the economic, environmental, and health benefits from adopting clean energy technologies while still protecting low-income households from higher bills.

1. Introduction

There is agreement among policymakers that a global transformation in how we produce and consume energy will be necessary to limit the risk of catastrophic climate change. This energy transition will require governments, firms, and households to convert energy sectors based on fossil fuels (transportation, heating, and industry) to use electricity. An increasing share of this electricity will be generated from renewable sources.

This paper studies a policy to encourage the energy transition for households in developing countries: electricity tariff reform. Incorporating developing country households will be essential for changing the world's energy systems. Total final energy consumption in developing economies is projected to grow at 1.6 percent per annum between 2019 and 2040, compared to an annual decline of 0.2 percent projected for advanced economies over the same period (IEA, 2020). Stifling this demand growth would be misguided, given the core role that energy plays in economic development (Lipscomb et al., 2013). Moreover, improved energy access will enable households to mitigate the worst effects of climate change (Davis and Gertler, 2015; Barreca et al., 2016).

Under an efficient electricity tariff, the marginal price of consumption equals the marginal cost of production, including emissions costs. Such an electricity price encourages consumers to make more efficient decisions about their usage of energy services. More importantly, consumers will make more cost-effective choices of energy-using durable goods, including the fuel type (for example,

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[☆] We thank seminar participants and discussants at the Inter-American Development Bank (IDB), ITAM, FGV CERI, the Boise State Energy Policy Conference, the Environment for Development annual meeting, the SETI workshop, the World Bank–Toulouse School of Economics #Infra4Dev conference, the EAERE annual meeting, and the Transportation and Public Utilities Group meetings, for their many helpful comments and suggestions. Pedro Liedo provided excellent research assistance. This paper was part of the IDB project "The Regulation of Public Utilities of the Future in Latin America and the Caribbean". We thank the IDB for their generous feedback and support for this research. McRae also gratefully acknowledges financial support from the Asociación Mexicana de Cultura, A.C.

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https://doi.org/10.1016/j.jeem.2021.102541
Received 18 April 2020
Available online 1 September 2021

choosing between an electric and a natural gas stove). These decisions can have long-lasting economic and environmental impacts because of the useful life of many durable goods (Davis and Kilian, 2011).

The problem with the existing electricity tariffs in virtually all jurisdictions is that the marginal price is too high. Most regulators set tariffs based on the average production cost, with the fixed costs of supplying electricity included in the per-unit price. Faced with these high electricity prices, consumers will make choices that are privately but not socially optimal. For example, they are likely to continue to choose cooking, transportation, and heating appliances that use fossil fuels, not electricity. Such choices will delay the transition to renewable energy. At the same time, high electricity prices encourage households to make investments to reduce their electricity purchases. These investments may represent a misallocation of resources that could otherwise support the energy transition. For example, residential solar installations may be privately but not socially optimal because the levelized cost of energy (LCOE) from utility-scale solar systems is significantly lower than the LCOE for rooftop systems (IRENA, 2021).

We study both the short-run and long-run distortions of the electricity tariffs in Colombia. The Colombian tariffs combine average cost pricing with a complex system of targeted subsidies and taxes. As a result, there is substantial variation across households in the marginal price of electricity, with some households paying prices three times higher than the marginal cost. We calculate an annual welfare loss of the short-run consumption distortions from these prices of more than US$80 million (Section 4). Using simulations of household-level adoption decisions, we compare the adoption of rooftop solar and electric stoves under the existing and efficient tariffs (Section 5). The current tariffs encourage the over-adoption of rooftop solar. At an installed solar system price of US$2500 per kilowatt, 12 percent of households would adopt rooftop solar systems under the existing tariff, compared to 3 percent under an efficient tariff.[1] Conversely, the current tariffs discourage the adoption of clean electric stoves. For a stove price of US$200, less than 1 percent of households would switch from natural gas to an electric stove under the existing tariff, compared to 21 percent under an efficient tariff.

Our analysis of how electricity mispricing delays the transition to renewable energy sources is relevant to industrialized and developing countries. However, because of the higher growth of energy demand expected in developing countries, setting an efficient electricity price is likely to deliver greater economic and environmental benefits than in industrialized countries. As households in developing countries earn higher incomes, many buy energy-using durable goods for the first time (Gertler et al., 2016). Starting with a clean appliance portfolio will be simpler than retrofitting or replacing an existing portfolio. Moreover, many countries lack the infrastructure to distribute fossil fuels (for example, gasoline refueling stations and natural gas pipelines). Electrifying household energy consumption would allow governments to "leapfrog" the need to build some fossil fuel infrastructure (van Benthem, 2015). Finally, there are direct environmental and health benefits to households from electrification. Many developing country households rely on traditional or fossil fuels for energy services such as cooking, heating, and lighting. In 2017, 1.64 million deaths were attributed to household air pollution from solid fuels (GBD, 2018), more than the number of deaths from unsafe water and sanitation. Barron and Torero (2017) provide experimental evidence of the improvement in indoor air quality from electrification, showing a 66 percent decline in particulate matter and an improvement in child health for electrified households.

Although economists since Hotelling (1938) have described the principles of efficient public utility pricing, this policy is rarely discussed in the context of the household energy transition. IEA (2020) lists 24 types of energy policy adopted by countries in 2019 and 2020, mostly efficiency standards and clean technology subsidies. Only one policy (carbon pricing) is directly related to energy prices.[2] High-income jurisdictions may have the institutional and fiscal capacity to correct their distorted energy prices using multiple layers of standards and subsidies. However, this is not the case for most developing countries. It is cheaper for governments to correct incentives by setting prices than by providing subsidies.

Although the potential economic and environmental benefits from electricity tariff reform are likely to be greatest in developing countries, there are also considerable challenges. Governments have long used utility tariffs to redistribute income. Most households in developing countries do not pay income tax, and (at least until the recent growth in conditional cash transfer programs) welfare payments to households are rare. In the case of Colombia, the neighborhood-level targeting of electricity tariffs has become deeply embedded in society. As a result, public utility tariff reforms are politically fraught. In many countries across the world, proposals to change electricity prices have incited riots and revolutions. An additional problem in developing countries is electricity theft through informal grid connections (Richter et al., 2020). Households with a low willingness to pay for electricity may prefer an informal connection instead of a formal connection with a fixed monthly charge.

We therefore study alternative electricity tariffs that provide efficient short-run and long-run incentives for households and also achieve the government's distributional objectives. Meeting these distributional objectives will be necessary for the tariff reform to be politically feasible. For Colombia, we show that charging an identical efficient tariff to all households would benefit households in the highest income decile by an average of more than US$8 per month, relative to the existing tariffs. In contrast, households in the lowest decile would be worse off by more than US$2 per month (Section 6). This difference between the highest and lowest deciles is halved under a policy that sets the same variable charge for everyone but sets the fixed charge based on our estimate of the household's willingness to pay for grid-supplied electricity at the marginal cost. Our results show that it is possible to transition to an efficient electricity tariff while still protecting low-income households from large increases in their bills.

This study contributes to the literature on the welfare distortions created by deviations from marginal cost pricing for public utility tariffs. Most of this literature focuses on short-run distortions in industrialized countries. Davis and Muehlegger (2010) show

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[1] Correcting this distortion does not necessarily mean that less solar energy will ultimately be consumed in Colombia, only that households demanding solar energy will find it more attractive to purchase it from lower-cost, utility-scale solar generation units.

[2] We note that policymakers should not consider carbon pricing in isolation from tariff reform proposals. In the presence of a pre-existing distortion such as an average cost tariff, adding a carbon tax may be welfare-reducing.

that residential natural gas consumers in the United States pay an average markup of 48 percent above private marginal cost, contributing to a deadweight loss of 3 percent of natural gas expenditure. Borenstein and Bushnell (2018) incorporate externalities into their analysis and show that for many parts of the United States, marginal electricity prices are close to social marginal cost. These previous studies focus on the short-run effect. Our analysis also considers the effect of price distortions on long-run electricity demand by calculating the incentives for households to invest in new technologies that will increase or decrease their electricity purchases.

The second contribution of our analysis is to the literature on the distributional effects of alternative tariff designs that reduce the distortions from non-marginal-cost pricing. Borenstein (2012) and Levinson and Silva (forthcoming) study the distributional implications of existing electricity tariffs in the United States. Borenstein and Davis (2012) show that moving to marginal cost pricing for natural gas, with cost recovery through fixed charges, would increase bills for two-thirds of households in the lowest income quintile. Burger et al. (2020) use data from an electric utility in Illinois to compare the effects of varying residential fixed charges based on demand, income, or geography, showing how this can mitigate much of the distributional effect of switching to marginal cost prices. Borenstein et al. (2021) study the retail rate design question for California, which has some of the highest residential electricity prices in the United States. They argue for income-based fixed charges or recovering these costs from state sales or income taxes. Income-based fixed charges are infeasible in a developing country context, where informal employment is common, and most workers do not pay taxes. Our study considers feasible alternative methods for varying the fixed charge based on the household's willingness to pay for grid-supplied electricity at an efficient price, with a theoretical justification from Wolak (2018), and compares their effects using data from all electric utilities in Colombia. These methods can be implemented in both industrialized and developing country contexts without the need to obtain sensitive data from customers, such as their income, or increase state sales or income taxes.

Most importantly, the existing literature on the efficiency and distributional effects of alternative tariffs focuses on industrialized countries. As discussed above, our analysis of these issues in a developing country setting is especially relevant. Although we focus on Colombia, our results can be generalized to many other countries that have similar tariff structures (Komives et al., 2005). Finding a politically feasible approach to reform these tariffs and encourage the transition to renewable energy sources will provide substantial economic and environmental benefits.

The remainder of the paper is organized as follows. Section 2 describes the regulatory environment and existing tariffs in Colombia. Section 3 describes the data used for our analysis. Section 4 shows our calculation of the marginal cost and the short-term distortions associated with the existing tariffs. Section 5 provides our analysis of the long-run distortions from the existing tariffs, focusing on the incentives for installing rooftop solar and buying an electric stove. Section 6 outlines our proposal for an efficient tariff, including the alternative methodologies for allocating fixed costs. Section 7 concludes.

2. Background on electricity tariffs in Colombia

Colombia is an upper-middle-income country with a population of 48.3 million in 2018, of whom 96.3 percent had access to electricity (DANE, 2020). Nearly all electricity users are connected to the national grid (the *Sistema Interconectado Nacional*). Restructuring of the electricity industry began in the 1990s. This process included the creation of an independent regulator, the introduction of a bid-based wholesale electricity market, and the privatization of government-owned firms. More than 82 percent of generation was supplied by hydroelectricity during the period from June 2016 to May 2017, although the share of hydro falls in years with lower rainfall (McRae and Wolak, 2016). Investment in nonconventional renewables (wind and solar) has been slower in Colombia than in other Latin American countries.

The primary regulator in the Colombian energy sector is the Energy and Gas Regulatory Commission (CREG, short for its Spanish name: *Comisión de Regulación de Energía y Gas*), which acts based on the policies set by the Ministry of Mines and Energy. Among other functions, CREG sets the regulated electricity tariff for households and other small consumers. Regulated retail tariffs consist of either a single variable charge with no fixed charge or a nonlinear price schedule with two marginal prices and no fixed charge. The base tariff is the sum of six components: generation (based on the wholesale market procurement costs for the retailer), transmission, distribution, retailing, allowed losses, and transmission restrictions. Distribution and transmission charges are set based on rate-of-return regulation.

There are about thirty regulated network operators in Colombia that distribute electricity to customers in a region. Each distribution firm also has a retailing operation that procures electricity from generators or the wholesale market. Although there is competition among retailers for large electricity consumers, households are supplied by the retailer associated with their local distribution utility. The base tariffs differ across utilities, mostly due to economies of scale in their distribution and retailing operations. In June 2017, the lowest base tariff was 12 U.S. cents per kWh, and the highest was 20 U.S. cents per kWh.[3],[4]

Colombia targets electricity subsidies by classifying neighborhoods into six socio-economic strata (*estratos*). Households in Strata 1, 2, and 3 face a two-tier increasing block tariff (Figure A1). The price for the first tier incorporates a subsidy of approximately 55 percent of the base tariff for Stratum 1, 45 percent for Stratum 2, and 15 percent for Stratum 3. The subsidized quantity is 130

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[3] Figure A2 shows the components of the base tariffs for each of the distribution utilities included in the analysis.

[4] We use the same exchange rate to convert from Colombian pesos to U.S. dollars throughout the paper: 2954 Colombian pesos per dollar. This was the mean exchange rate over the period covered by the household survey. The minimum and maximum values for the exchange rate were 2838 and 3188 pesos per dollar. Exchange rate data are from Banco de la República (2019b).

Table 1
Subscribers, consumption, and subsidies in the Colombian electricity market, June 2016–May 2017.

Customer type	No. of customers		Consumption	Subsidy per month	
	Million	% of total	kWh/month	US$/user	US$ million
Residential					
Stratum 1	3.73	27.3	142.4	9.15	34.2
Stratum 2	4.52	33.1	138.7	7.23	32.7
Stratum 3	2.70	19.8	150.6	2.34	6.3
Stratum 4	0.91	6.7	175.6	0.00	0.0
Stratum 5	0.36	2.6	212.6	(5.83)	(2.1)
Stratum 6	0.21	1.6	328.8	(8.31)	(1.8)
Non-residential	1.22	8.9	2144.2	(24.79)	(30.2)
Total	13.65	100.0	328.5	2.86	39.1

Notes: Data is calculated from the monthly reports of subscriber numbers, total consumption, and subsidy amounts, by retailer and municipality, from SSPD (2018). Negative values are shown in parentheses and represent the contributions to the cross-subsidy program.

kWh per month for households in highland areas (higher than 1000 meters above sea level) and 173 kWh per month in the warmer lowland areas. Households pay the base tariff for additional consumption above the subsidized quantity.

Households in Strata 5 and 6 and most non-residential users pay 20 percent above the base tariff for their entire consumption. The extra payment is used as a contribution towards the subsidies for the households in the lower strata. Households in Strata 4 neither contribute nor receive subsidies: they pay the base tariff for their entire consumption.

Many more households receive subsidies than make contributions. In 2016, 88 percent of households were classified in the subsidized Strata 1, 2, or 3 (Table 1). Households in Strata 5 and 6 had higher average consumption than the subsidized households, with Stratum 6 households consuming a mean of 329 kWh per month compared to a mean of 142 kWh per month for Stratum 1 households. Despite their higher consumption, the low proportion of households classified in the highest strata meant that their contributions only cover 5 percent of the subsidies.

For all except the largest utilities, the cross-subsidy contributions do not defray the cost of the subsidy transfers to the households in Strata 1 to 3. The subsidy deficit for each utility is covered by the redistribution fund known as the Solidarity Fund for Subsidies and Income Distribution (FSSRI, for its initials in Spanish: *Fondo De Solidaridad Para Subsidios y Redistribución de Ingreso*). Utilities with a contribution surplus pay the extra revenue into FSSRI, and utilities with a contribution deficit receive the difference from FSSRI. The central government provides a budget allocation to cover the overall FSSRI deficit. This loss was US$39.1 million per month in 2016–17, or about US$470 million over twelve months. Funding the shortfall requires about 0.8 percent of total government expenditure (Banco de la República, 2019a).

The current electricity tariffs in Colombia have several shortcomings. The deficit in the cross-subsidy program imposes an increasing fiscal burden on the Colombian government. Furthermore, the use of average cost pricing to set the base tariff, scaled up or down by the subsidies and contributions, generates a wedge between the marginal price and marginal cost of consumption. This distorts both short-run (Section 4) and long-run (Section 5) choices. Section 6 describes an alternative tariff that would provide incentives for efficient electricity consumption.

3. Data

We used household survey data to study the efficiency effects of the existing electricity tariffs and the distributional effects of efficient alternative tariffs. We used estimates of the marginal cost based on hourly data from the wholesale electricity market. We supplemented this information with data matched to each household on hourly demand, solar radiation, solar generation potential, natural gas tariffs, and gasoline prices.

The household data is from the National Household Budget Survey that was conducted between July 11, 2016, and July 9, 2017 (DANE, 2018).[5] The survey included household and dwelling characteristics, appliance holdings, and annualized income and expenditure. We used data for the municipality and stratum to match each household to its local utility and then to the electricity tariff faced in the month before the survey.

Using the self-reported electricity bill, we imputed each household's electricity consumption. For example, suppose a Stratum 2 household in Bogotá reports an electricity expenditure of 50,000 pesos in March 2017. We matched the municipality (Bogotá) to the electricity supplier (Codensa) and used the tariff sheets for that month (Enel, 2018). The Stratum 2 tariff was 245 pesos/kWh for the first 130 kWh of consumption per month and 454 pesos/kWh for additional consumption. The cost for the entire first block was 31,850 pesos (245 × 130). The survey household had 18,150 pesos of consumption on the second tier, or 40 kWh (18,150/454). The imputed monthly consumption for the survey household is 170 kWh (130 + 40).

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[5] The survey data contains 87,201 observations. After dropping households who do not have electricity or do not receive an individual electricity bill, among other reasons, there were 65,899 observations for the analysis. Appendix B provides details of the construction of the sample.

Table 2
Summary statistics for electricity consumption, income, and other household characteristics.

Variable	Min.	Mean	Median	Std. dev.	Max.
Electricity bill (US$/month)	0.68	17.35	12.83	17.13	358.44
Electricity usage (kWh/month)	10.07	155.69	134.01	114.64	1958.44
Average price (US cents/kWh)	6.43	10.39	9.29	3.17	23.44
Marginal price (US cents/kWh)	6.43	12.33	13.75	3.89	23.44
Natural gas bill (US$/month)	0.00	7.64	6.09	7.39	609.38
Natural gas connection (0/1)	0.00	0.68	1.00	0.47	1.00
Natural gas usage (cubic meters/month)	0.00	19.00	16.27	16.53	1473.94
Expenditure per person (US$000/month)	0.01	0.25	0.16	0.39	17.73
Household expenditure (US$000/month)	0.02	0.68	0.49	0.83	52.27
Household income (US$000/month)	0.00	0.82	0.52	1.19	74.06
Income per person (US$000/month)	0.00	0.30	0.17	0.55	43.00
Apartment (0/1)	0.00	0.41	0.00	0.49	1.00
Number of bedrooms in dwelling	1.00	2.10	2.00	0.90	24.00
Number of household members	1.00	3.44	3.00	1.71	22.00
Number of rooms in dwelling	1.00	3.55	3.00	1.20	41.00
Elevation (km)	0.00	1.31	1.30	0.98	3.06
Solar generation (MWh/kWp)	1.19	1.49	1.49	0.09	1.75
Car (0/1)	0.00	0.16	0.00	0.37	1.00
Gasoline price (US$/gallon)	1.82	2.63	2.65	0.21	3.13
Refrigerator (0/1)	0.00	0.88	1.00	0.32	1.00
Air conditioner (0/1)	0.00	0.04	0.00	0.20	1.00
Television (0/1)	0.00	0.94	1.00	0.23	1.00
Washing machine (0/1)	0.00	0.66	1.00	0.47	1.00

Notes: The table shows summary statistics for selected variables in the household sample. The mean, median, and standard deviation are calculated using the survey sampling weights. Number of observations = 65,899.

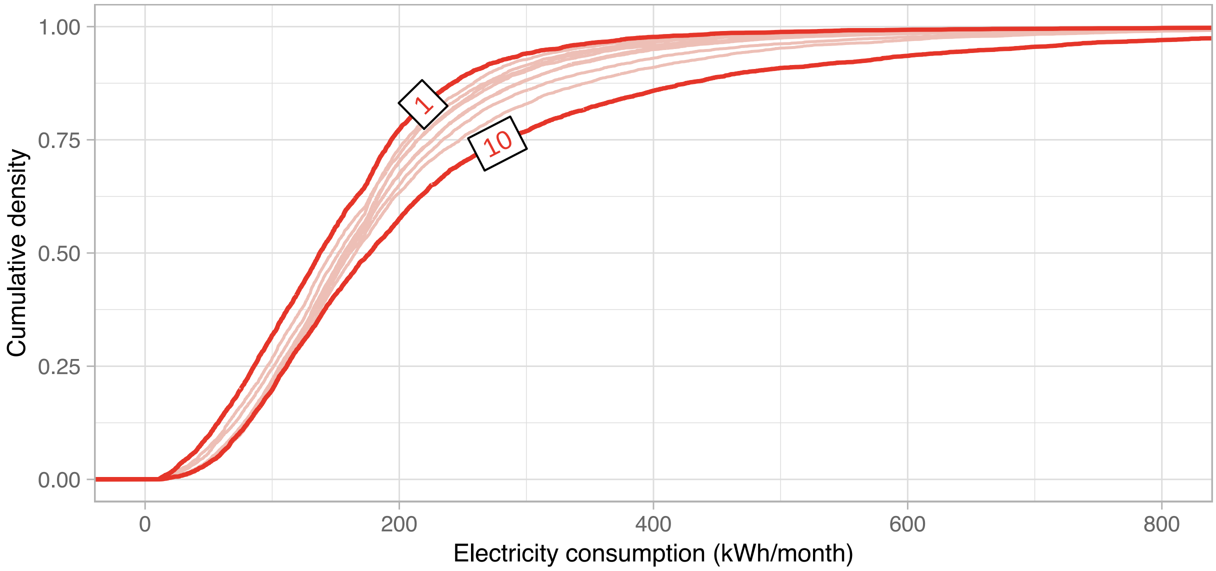

Fig. 1. Cumulative distribution of household electricity consumption, by income decile.
Notes: Each line shows the cumulative distribution of electricity consumption for one income decile, with the thicker lines indicating the distribution for the lowest and highest income deciles. Values above 800 kWh/month are not shown on the figure but are included in the calculation of the cumulative density.

The mean electricity bill is US$17 per month, compared to a mean household total expenditure of US$680 per month (Table 2). The mean electricity consumption is 156 kWh per month, implying an average price of about US$0.11 per kWh. The marginal price exceeds the average price because of the increasing block tariff faced by most households.

Fig. 1 shows the cumulative distribution of monthly household electricity consumption in Colombia, split by income decile. Higher-income households use more electricity than poorer households, with the distribution for decile ten households lying to the right of the lower deciles. However, consumption also varies within each decile. Over 50 percent of the decile ten households consume less than 200 kWh per month. About 20 percent of the decile one households consume more than 200 kWh per month.

We supplemented the survey and tariff data with information from other sources. We extracted the annual solar generation potential from the Global Solar Atlas (World Bank Group, 2017) and applied a 5 percent discount to reflect the energy production inefficiencies associated with small rooftop residential systems relative to larger systems.[6] We assigned each household the mean solar generation potential of the largest urban area in its municipality. Annual solar generation potential from a 1 kW panel varies between 1.19 MWh and 1.75 MWh, equivalent to a capacity factor of between 14% and 20% (Table 2).

We converted the annual solar potential to an hourly estimate using measurements of hourly solar radiation at 95 locations (IDEAM, 2020). We calculated an hourly scale factor by dividing the sum of solar radiation in an hour by the annual solar radiation. We matched each municipality to the closest weather station. The timing of peak solar generation depends on longitude, which determines when the sun is directly overhead (Figure A3).

We also converted the imputed monthly electricity consumption to an hourly estimate. Residential electricity consumers in Colombia do not have real-time meters. Instead, we used the hourly aggregate electricity demand for the regulated consumers served by each utility, from June 2016 to May 2017 (XM, 2019a). We assigned each household the mean hourly load shape of its utility. Electricity demand is highest in the early evening between 7:00 PM and 8:00 PM (Figure A4).

For our analysis of cooking fuel choices (Section 5.2), we estimated the natural gas consumption using the same imputation procedure that we used for electricity. The natural gas tariffs have an increasing block structure targeted by neighborhood. We used the self-reported amount of the most recent natural gas bill for the household survey data. We matched this to the natural gas tariff for the month, year, and municipality and then calculated the implied natural gas quantity. The median natural gas bill is US$6 and the median consumption is 16 cubic meters per month.

Finally, we used wholesale market data to calculate the marginal cost of electricity consumption. This data included hourly market prices and daily generator offer prices (XM, 2018). We also used the hourly real (actual output) and ideal (projected output before physical operating constraints are accounted for) generation of each plant and, for calculating emissions, the daily fuel consumption by plant (XM, 2019c). We converted the fuel consumption to carbon dioxide emissions using standard emissions coefficients (EIA, 2018b) and allocated these across hours in proportion to hourly generation. Section 4 describes the marginal cost calculation using this data.

4. Short-run implications of inefficient retail pricing

An efficient price schedule for electricity is one in which the amount that the consumer pays for one additional unit of consumption (the marginal price) is equal to the cost of supplying that additional unit of consumption (the marginal cost). If marginal prices are higher or lower than marginal costs, then there will be a distortion in the consumption decision. In particular, if the marginal price exceeds the marginal cost, then the household will choose to consume too little electricity.

4.1. Marginal cost of electricity

An increase in electricity consumption from switching on a light is instantly matched by higher output from a generation plant. The marginal cost of consumption is the cost of generating one extra unit of electricity and delivering it through the grid to the household. We consider four components of this marginal cost: system price, reconciliation payments, line losses, and the greenhouse gas externalities.

Generators in the Colombian market compete to supply electricity by submitting price and quantity offers for each generation unit they own to a multi-unit, uniform price auction that takes place each hour of the day. The system operator orders the quantity offers from the lowest to the highest offer price. The offer price where this aggregate offer curve crosses the level of electricity demand during that hour is the market-clearing price. The quantity offers of all plants with offer prices at or below the market-clearing price are accepted in this auction and paid the market-clearing price. The quantity accepted in this auction is called the *ideal generation* of the unit because that is what it could produce if there were infinite transmission capacity in Colombia.

Finite transmission capacity between locations in Colombia and constraints on the operation of the grid often prevent certain generation units from producing their ideal generation. Higher cost generation units must be operated to replace the energy that these units are unable to supply because of the configuration of the transmission network or other system operating constraints.[7]

To determine which units must reduce their output and which units must increase their output relative to the ideal generation, the system operator minimizes the cost of serving actual demand throughout the transmission network, accounting for all of the transmission constraints and other relevant operating constraints (McRae and Wolak, 2016). This process yields the actual output level of all generation units in Colombia during the hour. If a generator is required to produce more than its ideal generation, it

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[6] The Solar Atlas reports the amount of electricity that could be generated at a location, assuming an optimal installation angle for the solar panels. The calculation is based on multi-year time series of solar radiation and air temperature. It also accounts for hill-shading effects and other common reasons for losses at a location, such as snow or dust. The spatial resolution of the Global Solar Atlas is approximately 1 × 1 kilometer. We calculated the mean potential for the grid cells in the largest urban area.

[7] Electricity market designs differ in the extent to which they explicitly account for these transmission constraints in prices. In a nodal price market, every location on the transmission grid has an hourly price. This price is the marginal cost of supplying one extra megawatt-hour at that location in that hour, accounting for all transmission constraints and losses. Bohn et al. (1984) show how to derive the nodal pricing formula from the solution to the constrained optimization problem for allocating generation to each plant.

Table 3
Estimation of marginal emissions.

	Generation (MWh)				CO_2 emissions (t)	
	Hydro (1)	Natural gas (2)	Coal (3)	Liquids (4)	(5)	(6)
Total load (MWh)	0.888 (0.019)	0.076 (0.012)	0.026 (0.013)	0.010 (0.005)	0.069 (0.016)	
Thermal generation (MWh)						0.659 (0.013)
Month-of-sample × Hour	Y	Y	Y	Y	Y	Y
Observations	35,064	35,064	35,064	35,064	35,064	35,064
R^2	0.957	0.820	0.736	0.829	0.883	0.979
Within R^2	0.753	0.041	0.009	0.003	0.034	0.827

Notes: Each observation is one hour, for the four-year period from January 2015 to December 2018. The dependent variable in Models 1 to 4 is the total generation in each hour from each fuel type. The dependent variable in Models 5 to 6 is the estimated total carbon dioxide emissions in each hour. "Liquids" may be diesel, fuel oil, or kerosene. Newey–West standard errors with 48 lags are shown in parentheses.

receives a reconciliation payment for the difference.[8] We used an estimate of the average net reconciliation payments each hour as the second component of marginal cost.[9] Because this value is the same for all regions, it does not account for the geographical variation in marginal costs caused by transmission constraints.

The marginal cost of consuming an additional kilowatt-hour will be higher than the marginal cost of generating an additional kilowatt-hour due to transmission and distribution losses. These losses are an unavoidable consequence of resistance in the cables used to transmit electricity, causing some of the electricity to be converted to heat. If losses are 10 percent, then for a household to consume 1 kWh, the generation plants will need to produce $1/(1-0.1) = 1.11$ kWh of electricity. In that case, if the marginal cost of generating 1 kWh is 100 pesos, the marginal cost of consuming 1 kWh will be 111 pesos. Resistance (and hence losses) increases with the square of the amount of electricity flowing through a wire. This physical relationship means that losses will be greater during peak demand hours when electricity flows are higher.

We used the average hourly transmission losses allocated to retailers (1.5 percent of demand) as a proxy for the marginal transmission losses. For marginal distribution losses, we used estimates from Borenstein and Bushnell (2018) of the marginal losses in the distribution networks in the United States.[10] They estimate a distribution of marginal distribution losses with a mean of 8.87% and a standard deviation of 1.83%. We used these parameters to calibrate the marginal distribution losses in Colombia, allocating losses to hours using the system load shape.[11]

The final component of the marginal cost is the external cost of emissions from electricity generation. We used within-month-and-hour variation in electricity demand to estimate marginal emissions (Graff Zivin et al., 2014; Callaway et al., 2018), as shown in Eq. (1). We estimated the model using four years of data from 2015 to 2018, centered on the period of our household survey data.

$$y_t = \beta Load_t + \omega_{h(t)m(t)} + \varepsilon_t \tag{1}$$

Here y_t is either the generation by fuel type, or carbon dioxide emissions, in hour-of-sample t. The variable $Load_t$ is the total system load (including losses) in MWh in hour-of-sample t. The fixed effects $\omega_{h(t)m(t)}$ are by hour-of-day and month-of-sample. That is, there is a fixed effect for 12:00 AM in January 2015, 1:00 AM in January 2015, and so on. In total there are $24 \times 12 \times 4 = 1152$ fixed effects. The coefficient β is the incremental generation (or emissions) in response to a 1 MWh increase in demand.

Estimation results are shown in Table 3. In the Colombian electricity market, a small change in electricity demand within an hour and a month is mostly matched by a change in hydroelectric generation. Hydroelectric plants are flexible and can quickly increase or decrease output in response to demand fluctuations. A 1 MWh increase in load predicts a 0.888 MWh increase in hydro generation (Column 1). The remainder of the increase in load is met by a small increase in thermal generation, mostly from natural

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[8] Positive reconciliation payments, for actual generation exceeding ideal generation, are calculated based on the estimated variable cost of the generation unit. Generation units that produce less than their ideal generation must refund the difference between their ideal and actual generation times the market-clearing price to the system operator.

[9] For each plant with output exceeding its ideal generation, we estimated the reconciliation payments by multiplying the hourly excess generation by the difference between the plant's offer price and the system price, which is how this payment is computed by the market operator. We divided the total payments by aggregate generation to estimate the mean net reconciliation payment.

[10] Data on the hourly quantity of distribution losses does not exist because it would require hourly information on all injections and all withdrawals from the network. This calculation would only be possible if all customers in the network had hourly meters. It is even difficult to calculate the average distribution losses in Colombia. The annual reported network losses include both technical and non-technical losses. The technical losses are the physical losses from electricity flowing through a wire. The non-technical losses include unmetered withdrawals of electricity by consumers, including households with informal connections to the grid. For calculating the marginal cost of electricity, only the technical losses are relevant.

[11] We ranked every hour in our sample in order of total electricity demand. Given the percentile rank of each hour, we used the inverse cumulative normal distribution function with the Borenstein and Bushnell (2018) parameters to calculate the corresponding marginal distribution losses. We truncated the estimates at the minimum and maximum of the estimated losses in their paper.

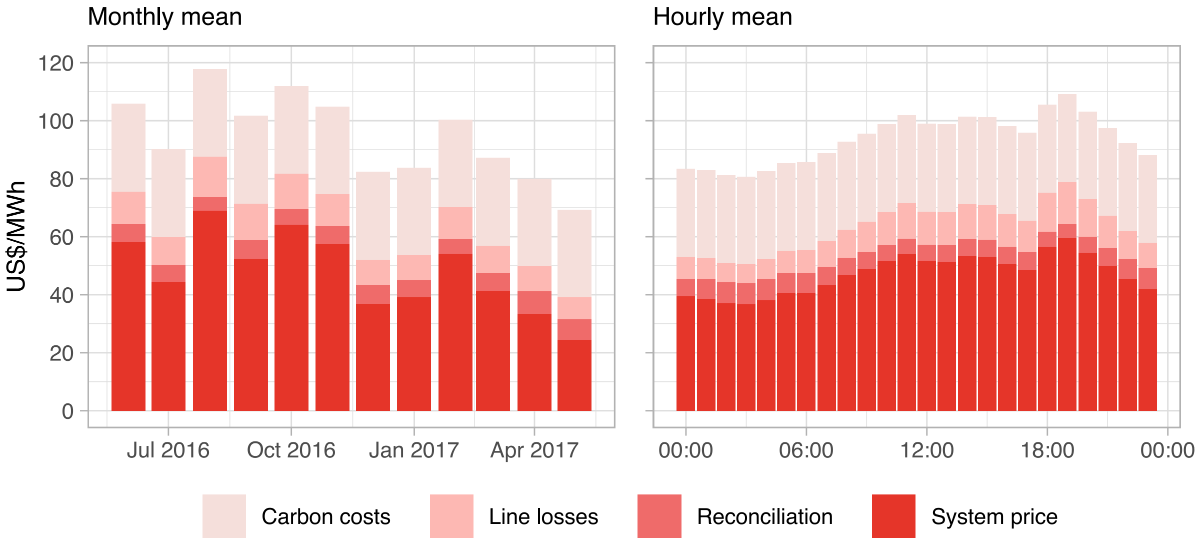

Fig. 2. Marginal costs for electricity consumption in Colombia, by month and by hour, for June 2016–May 2017.
Notes: The left panel shows the monthly means of the four components of the marginal cost of electricity. The right panel shows the hourly means of the marginal cost components. The marginal costs in both panels are weighted by the generation in each hour.

gas (Column 2). Given that changes in hydro generation satisfy most of the change in load, direct marginal emissions are low. A 1 MWh increase in load leads to a 0.069-ton increase in carbon dioxide emissions in that hour (Column 5).[12]

Although there are no direct emissions associated with the additional hydroelectric generation, hydroelectric systems are constrained by the total amount of water available. Producing an extra kilowatt-hour from hydroelectricity today will reduce the water available to produce electricity tomorrow. If the constraint on the available water is binding, then a marginal increase in demand will have to be met later from fossil fuel generation plants.[13]

We made the conservative assumption that all marginal changes in electricity demand will be matched by a marginal change in thermal generation, potentially days or months later.[14] This can either be direct (Columns 2 to 4 of Table 3) or indirect (due to a binding constraint on hydroelectric availability). Given this assumption, the relevant marginal emissions factor is the change in carbon dioxide emissions from an increase in thermal generation. A 1 MWh increase in thermal generation leads to a 0.659-ton increase in carbon dioxide emissions (Column 6). We converted this marginal emissions factor to a monetary value using a social cost of carbon of US$46 per ton.[15] Our assumption that there is a binding constraint on hydro availability means that this calculation is an upper bound on the hourly marginal emissions.

In many electricity markets, there are large differences in marginal emissions across hours of the day (Graff Zivin et al., 2014). These differences are important for evaluating the environmental effects of electricity storage, electric vehicle charging, time-varying pricing, and other policies that shift consumption within the day. In Appendix C, we report the results from estimating marginal generation and emissions by the hour of the day. We show that marginal generation and emissions in Colombia are similar for all hours of the day. This result is to be expected given the large share of energy supplied by hydroelectric resources. Consequently, we assumed that the emissions factor is the same every hour, both because the marginal generation and emissions are similar across hours and also because the indirect emissions from an increase in demand may occur days or even months later.

We calculated a mean marginal cost for our study period of 9.5 U.S. cents per kWh: 4.8 cents for the system price of generation, 0.6 cents for the positive reconciliation payments, 3.0 cents for the carbon price, and 1.0 cents for the marginal losses. Averaged

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[12] The only external cost from electricity generation that we include is the cost of carbon dioxide emissions. Other pollutants from fossil fuel plants, including sulfur dioxide, nitrogen oxides, and particulate matter, create local air pollution that may harm the surrounding population. Several studies quantify the marginal damages of these other pollutants in the United States using models of their movement through the atmosphere (Muller and Mendelsohn, 2009; Holland et al., 2016). Unfortunately, data on power plant emissions are not collected in Colombia, making it difficult to estimate the marginal emissions of local pollutants.

[13] If the hydro constraint is not binding, then we should observe water being released from reservoirs without producing electricity ("spill"). Between June 2016 and May 2017, the energy lost through hydro spill was 1241 GWh, or 2.3 percent of the hydro generation for the period (XM, 2019b). If there were hours when the hydro constraint was not binding, meaning an increase in load could have been supplied by the water that would otherwise have been wasted, then the marginal emissions in those hours would have been zero.

[14] Castro (2019) studies the shifting of emissions across hours of the day through the reallocation of hydro production in the Californian electricity market. In the Colombian market, there is seasonal variation in hydro inflows and reservoir levels, meaning that there may be a delay of six months or more between the demand shock and the resulting thermal generation.

[15] Our estimate of the social cost of carbon is the average value for 2017 with a 3 percent discount rate, from the Interagency Working Group (2016), inflated from 2007 to 2017 dollars using the GDP deflator from BEA (2021).

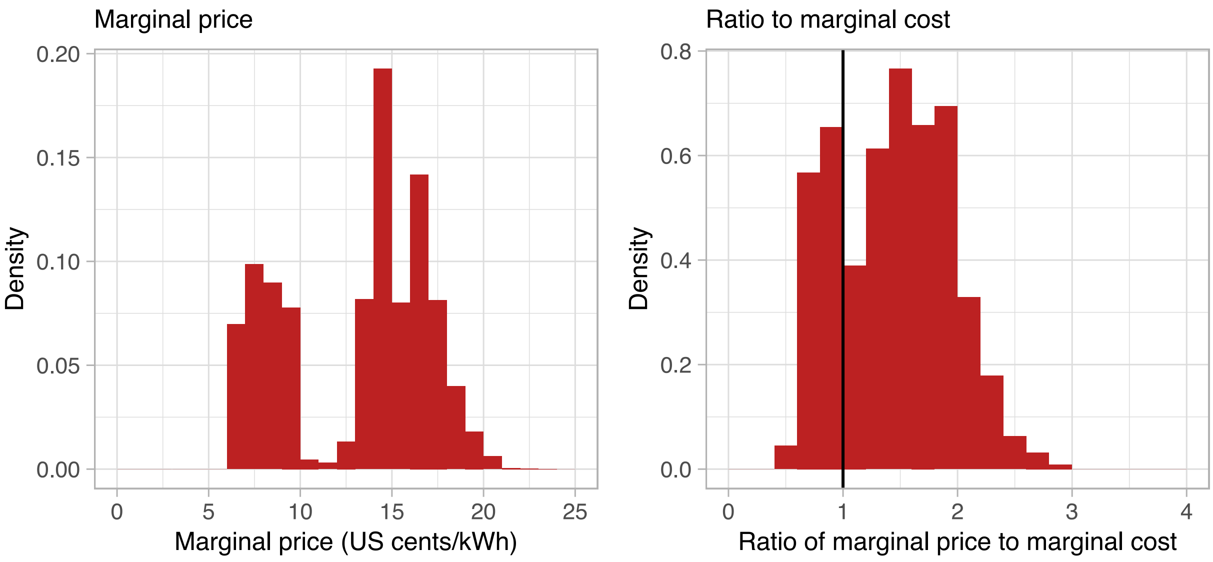

Fig. 3. Distribution of marginal electricity prices faced by households in Colombia, 2016–17.
Notes: Marginal prices for each household are determined based on the household stratum, the imputed consumption from the National Household Budget Survey, and the tariff schedule from the household's electricity distributor. The left panel shows the distribution of the marginal prices in U.S. cents/kWh. The right panel shows the distribution of the ratio of marginal price to the monthly mean marginal cost. All observations are weighted by the survey sample weights so that the figure is representative of the population of grid-connected Colombian households.

over the year, this is the efficient price that Colombian households should have paid for their electricity consumption. Charging a higher or lower price would create distortions in household consumption decisions.

There is considerable variation in the marginal cost over months of the year and hours of the day. Fig. 2 shows the composition of marginal costs for each month in the sample (left panel) and the mean by the hour of the day (right panel). The marginal cost was highest in August 2016 (nearly 12 cents per kWh) and lowest in May 2017 (less than 7 cents per kWh). These differences are mostly due to changes in generation costs over the sample period, arising from changes in the opportunity cost of using water for hydro generation and changes in the price of fossil fuels for thermal generation. Across hours of the day, the mean marginal cost was lowest at 3:00 AM and highest at 7:00 PM. This variation reflects differences in marginal generation costs due to the pattern of electricity demand across the day. By assumption, carbon costs are the same every hour, and the reconciliation costs are relatively stable across the day. The differences in marginal losses exacerbate the intraday variation in system prices. Marginal losses are higher in high-demand hours, exactly when generation costs are highest.

4.2. Marginal price of electricity

A small increase in the electricity consumption of a household will increase the total monthly bill. The marginal price is the increase in the bill for a one-kilowatt-hour increase in consumption. For the households in Strata 4 to 6, the marginal price is the uniform price per kilowatt-hour from the tariff schedule. Households in Strata 1 to 3 face a nonlinear tariff and so their marginal price will depend on their consumption (Figure A1). We used the imputed consumption from the survey to identify the price tier for the household and so the marginal price that they face.

The distribution of marginal prices is shown in the left panel of Fig. 3. The lowest marginal price observed in the data is 6.4 U.S. cents per kWh. The highest marginal price in the data is more than three times higher: 23.4 cents per kWh. For comparison, the average retail price for residential consumers in the United States during 2017 was 12.9 cents per kWh (EIA, 2018a).

We also compare the mean marginal cost for the survey month to the marginal price faced by each household (right panel of Fig. 3). A ratio of one means that the marginal price for the household is equal to the marginal cost. A ratio of less than one means that the marginal price of consumption is below marginal cost, so the household consumes too much electricity. A ratio greater than one means that the marginal price exceeds marginal cost, so the household consumes too little electricity.

For most households, the marginal price they face is too high. In the extreme, some households face a price that is three times greater than the marginal cost. These households are in Strata 5 and 6 in electricity distribution territories with high costs. Conversely, a minority of households face a price below marginal cost. These are households in Strata 1 or 2 with low consumption that places them on the subsidized first price tier, served by utilities with a low regulated base price.

Table 4
Deadweight loss from non-marginal-cost electricity pricing, assuming linear demand.

	Mean US$ per household			Share of expenditure		
	DWL_{avg}	DWL_{resid}	DWL_{total}	DWL_{avg}	DWL_{resid}	DWL_{total}
Price elasticity: −0.15						
Stratum 1	0.22	0.03	0.24	1.8%	0.2%	2.0%
Stratum 2	0.20	0.03	0.23	1.3%	0.2%	1.5%
Stratum 3	0.27	0.03	0.30	1.2%	0.1%	1.3%
Stratum 4	0.41	0.04	0.44	1.3%	0.1%	1.4%
Stratum 5	0.72	0.03	0.75	2.0%	0.1%	2.1%
Stratum 6	1.06	0.06	1.12	1.9%	0.1%	2.0%
Total	0.25	0.03	0.28	1.4%	0.2%	1.6%
Price elasticity: −0.30						
Stratum 1	0.43	0.05	0.49	3.5%	0.5%	4.0%
Stratum 2	0.41	0.06	0.47	2.7%	0.4%	3.1%
Stratum 3	0.53	0.06	0.59	2.4%	0.3%	2.7%
Stratum 4	0.81	0.08	0.89	2.5%	0.2%	2.8%
Stratum 5	1.44	0.06	1.50	4.1%	0.2%	4.2%
Stratum 6	2.12	0.11	2.23	3.8%	0.2%	4.0%
Total	0.50	0.06	0.56	2.9%	0.3%	3.2%

Notes: DWL_{avg} is the welfare loss due to the difference between the marginal price and the monthly mean marginal cost. DWL_{resid} is the welfare loss from the differences each hour between marginal cost and the monthly mean marginal cost. The first three columns show the mean deadweight loss in each category, in US$ per household per month. The second three columns show the deadweight loss as a percentage of total monthly expenditure in each category.

4.3. Short-run distortion from inefficient prices

Households will consume the efficient quantity of electricity only if they face a marginal price equal to marginal cost. Because of the gap between the real marginal price and the marginal cost (Fig. 3), the difference between the observed and the efficient level of consumption creates the welfare loss from the mispricing of electricity. Calculating this loss requires additional assumptions about the household's demand for electricity. We only observed one point on each household's demand curve: the marginal price they face p_0 and their consumption at that price q_0. With an assumption for the price elasticity of demand at (q_0, p_0), we calibrated both a linear demand curve and a constant elasticity demand curve passing through that point. We show results for two assumptions for the price elasticity of demand: −0.15 and −0.30.[16]

Because the marginal cost of supplying electricity varies each hour, the efficient price and consumption will also be different each hour. The total deadweight loss for a month, DWL_{total}, will be the sum of the hourly deadweight losses calculated from the difference between the time-invariant marginal price and the time-varying marginal cost. Borenstein and Bushnell (2018) decompose DWL_{total} into two components. DWL_{avg} is the deadweight loss from the difference between the marginal price and the quantity-weighted mean marginal cost for the month. DWL_{resid} is the sum of the hourly deadweight losses from the difference between the mean marginal cost and the hourly marginal cost. Appendix D provides additional discussion of this decomposition and the deadweight loss calculation.

For the linear demand model, DWL_{total} for households in Strata 1 and 2 is between 23 and 49 U.S. cents per month (Table 4).[17] The deadweight loss for these households is small because their demand for electricity is low and the difference between their marginal price and marginal cost is also low. At the other extreme, DWL_{total} for households in Stratum 6 is between US$1.12 and US$2.23 per month. These households have a higher consumption of electricity and face the largest difference between marginal price and marginal cost. As a share of monthly electricity expenditure, DWL_{total} is relatively flat across the six strata, with an average deadweight loss of 3.2 percent of expenditure for a price elasticity of −0.30. The aggregate annual deadweight loss for the 12.43 million residential consumers in Colombia is US$83.5 million.

Most of the total deadweight loss is caused by the difference between the marginal price faced by the household and the mean marginal cost for the month. The welfare losses from the hourly variation in marginal costs, DWL_{resid}, comprise about 10 percent of DWL_{total}. This result suggests that the largest gains from reforming electricity pricing in Colombia will come from setting the correct time-invariant price each month. The additional gains from implementing real-time pricing would be small: no more than 0.5 percent of electricity expenditure. This result does not even account for the additional capital and administrative costs of using time-varying prices. Our analysis of alternative tariffs in Section 6 only considers time-invariant tariffs.

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[16] Researchers agree that electricity demand is fairly price-inelastic. Miller and Alberini (2016) show how elasticity estimates are sensitive to modeling choices related to aggregation, unobserved heterogeneity, and instrumental variables. They recover a range of estimates for the United States of −0.2 to −0.8. For Colombia, McRae (2015) uses household billing data to estimate a mean elasticity of −0.32, with demand for households in Strata 1 and 2 being the most price-inelastic.

[17] The larger estimate is for the assumption of a price elasticity of −0.30. If demand is more price elastic, the difference between the actual and the efficient consumption is larger, and so the deadweight loss is larger. If demand were perfectly inelastic, there would be no deadweight loss.

Our result about the small benefits from real-time pricing may not generalize to other settings. Colombia is a hydro-dominated system. Both the opportunity cost and the avoided emissions from using water are the same every hour. This means that the hourly variance in marginal cost is small (Fig. 2) compared to the difference between price and the mean marginal cost (Fig. 3). In markets without hydro or other large-scale storage technologies, the requirement to exactly balance supply and demand can lead to large fluctuations in marginal cost and marginal emissions within a day. Increasing penetration of intermittent renewables may exacerbate these fluctuations and further increase the potential benefits from real-time pricing in those markets.

For our analysis, we assumed that households choose their consumption quantity based on the marginal price they face. Ito (2014) shows that households in southern California responded to the average price, not the marginal price, in a setting with a complex five-tier increasing block tariff. For our Colombian data, the marginal and average prices are the same for 55 percent of households. The remaining households are on the second tier of an increasing block tariff with only two tiers. For nearly all of these households, their average price is closer than their marginal price to the marginal cost. Therefore, if some households respond to average rather than marginal prices, then the short-run deadweight losses in Table 4 and the long-run distortions in Section 5 would be smaller than what we estimate.[18]

The results in Table 4 quantify the magnitude of the short-run distortions from pricing electricity above or below marginal cost. In the short run, electricity demand is assumed to be constant, and the mispricing causes the household to move along their demand curve. In the long run, the household might adjust their bundle of energy-using durable goods, leading to a shift in or out of the short-run electricity demand curve. In other words, electricity demand may be more price elastic in the long run, meaning that welfare distortions are potentially much larger than shown in Table 4. The next section discusses the relationship between electricity tariffs and household investment decisions.

5. Long-run implications of inefficient retail pricing

The most economically consequential energy consumption decisions made by households are the choice of energy-related durables. For example: What type of car to buy? Whether to install energy-efficient materials? What type of cookstove to use? These decisions constrain the household's short-run decisions and adverse environmental impacts for years or even decades. If the household decides to buy a fuel-inefficient car, this will have a greater effect on gasoline consumption over the following years than minor changes in driving habits.

In this section, we analyze the relationship between the electricity tariff structure in Colombia and two types of choices that may be made by households: whether to install rooftop solar and whether to buy an electric stove. The incentives created by non-marginal-cost pricing operate in opposite directions for these decisions. If households pay a marginal price for electricity that exceeds social marginal cost, there will be too much investment in rooftop solar systems and too little investment in electric stoves relative to the socially optimal level of investment.

5.1. Adoption of rooftop solar

We modeled the market for residential rooftop solar in Colombia under two tariff assumptions. First, we used the existing electricity tariffs with the 2018 regulations on the pricing of distributed generation. Second, we used our proposed efficient tariff based on the social marginal cost of electricity. For the second tariff assumption, excess solar generation is priced in a net metering framework, with all sales and purchases of electricity occurring at the marginal cost price. We show how the tariff structure interacts with the solar adoption potential.

Our analysis complements the existing research on the residential solar market in Colombia (Castaneda et al., 2017b; Jimenez et al., 2016; Castaneda et al., 2017a, 2018; Cardenas et al., 2017). These papers adopt a system dynamics framework that allows simulation of feedback effects over a multidecadal time horizon. Solar adoption in these papers follows a diffusion model, and all assumptions and variables are national-level aggregates. In contrast, our analysis models the adoption decision at a household level, using current data on tariffs, consumption, solar potential, and installation eligibility. This modeling choice allows us to examine the heterogeneity in adoption potential across households. We do not attempt to predict the development of the solar market, which will depend on the uncertain future prices of solar installations.

CREG Resolution 30 of 2018 defined the rules for paying small renewable producers, including households with rooftop solar installations (CREG, 2018). Distributed generators use two meters: one to record the power withdrawn from the grid and the other to record the power sent to the grid. There are three parts of the calculation of the monthly bill:

1. For the hours with self-generation less than consumption, no electricity is sent to the grid, and the electricity withdrawn from the grid is reduced by the amount of the generation. This offset occurs "behind the meter" and is not observed by the retailer. The consumer benefits by avoiding the full retail price on the self-generated units.

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[18] Our alternative tariffs in Section 6 combine a fixed charge with a uniform variable price. Ito and Zhang (2020) use a heating price reform in China to show that Chinese households distinguished between the fixed and variable components of a similar two-part heating tariff. That is, the households responded to the marginal price of heating, not the average price.

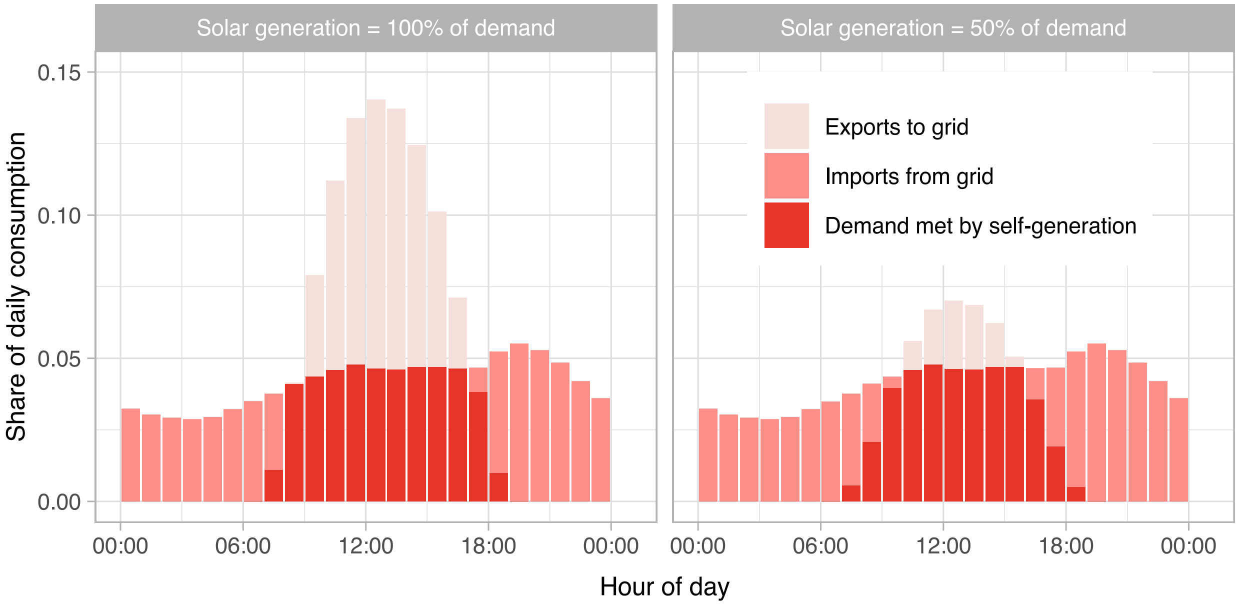

Fig. 4. Calculation of hourly excess solar generation, for different levels of household generation and consumption.
Notes: The mean hourly solar generation is from IDEAM (2020) and the mean hourly demand is from XM (2019a). See the discussion in Section 3. Hourly solar generation is scaled up or down depending on the assumed generation relative to demand.

2. For the hours with self-generation greater than consumption, the excess generation is exported to the grid. As long as the total amount of exports in the billing period is less than the total amount of imports, the exports are subtracted from the imports to calculate the monthly bill. However, the customer pays the retailing component of the regulated tariff on the quantity of exported generation.[19]
3. If the total exports in the billing period exceed the total imports, the customer receives the average wholesale electricity price for the surplus generation.

We have the annual solar generation potential and the monthly electricity consumption for each household (Section 3). We assumed that annual consumption is twelve times the monthly electricity consumption.[20] We imputed hourly electricity consumption and solar generation using the load shape of the household's retailer and the hourly solar radiation at the closest weather station. We limited our analysis sample to the 30 percent of households that could plausibly adopt private residential solar systems.[21]

Under the existing tariff, the electricity bill for households with solar will depend on the match between their hourly generation and consumption. Suppose annual generation is 50 percent of annual consumption (right panel of Fig. 4). There will be six hours in the middle of the day when the generation completely covers the household's consumption and the household sends its excess output to the grid. Of the daily solar generation, 81.1 percent covers the household's consumption and offsets the hourly imports from the grid. The remaining 18.9 percent is the excess generation sent back to the grid in the middle of the day. Based on the 2018 regulations, the excess 18.9 percent will be charged the retail component of the base regulated price. The household's electricity bill will be calculated using the usual tariff for the 50 percent of consumption that is not matched by self-generation, plus the retail charge for the 18.9 percent of exported generation.

Suppose instead that annual generation is equal to annual consumption (left panel of Fig. 4). In this case, the billed consumption for the year will be zero because the generation cancels out the demand. However, the household will still pay the retail charge for the generation sent to the grid: 52.7 percent of the total solar generation. This charge means that the household will still pay a positive, albeit smaller, electricity bill. If total solar generation exceeds demand, the household is paid the mean wholesale price for its surplus output, and the electricity bill may be negative.

Investing in solar will be optimal if the present value of the electricity bill savings exceeds the initial capital cost of installing solar. We explored the sensitivity of our results to two essential parameters: the discount rate and the solar capital cost. For the

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[19] The retailing component of the tariff covers the cost of metering, billing, financing, and customer service for the electricity retailer, as well as a charge for the wholesale market operator. It is set by price-cap regulation (that is, the retailing component is updated from a base level by inflation, less an expected efficiency improvement). The charge varies across retailers. During 2016–17, the mean retail charge was 2.4 US cents/kWh, with a range from 0.8 to 4.7 US cents/kWh.

[20] This assumption is less problematic in Colombia than it would be in the United States because the tropical climate means there is limited seasonal variation in electricity demand.

[21] We focused on owner-occupied houses and not apartments. Because of the weight-bearing requirements for solar installations, we limited our sample to houses with brick or concrete block walls, as in Hancevic et al. (2017). The survey does not have information about the roof material.

Table 5

Share of Colombian households for whom rooftop solar adoption would be privately optimal, for different tariff types and solar system prices.

System price	Adoption (%)		Solar generation (kWh/kWp)		Income (US$/person)	
(US$/kW)	Existing	Efficient	Existing	Efficient	Existing	Efficient
500	31.3	31.3	1495.2	1495.2	283.2	283.2
1000	31.2	31.3	1495.4	1495.2	283.4	283.2
1500	22.4	30.5	1506.6	1497.8	336.6	280.1
2000	15.4	17.4	1510.2	1510.7	395.1	267.9
2500	12.3	3.2	1513.1	1576.4	433.5	254.5
3000	8.2	0.0	1527.0		461.4	
3500	2.5	0.0	1541.9		630.5	
4000	0.4	0.0	1521.6		1118.5	

Notes: Each row shows the results for the optimal adoption of solar panels for a different system price, assuming a 5% real discount rate and a 30-year panel life. The adoption columns show the percentage of Colombian households who live in an owner-occupied house and for whom the net present value of installing solar is positive. The "existing" column shows the results for the current nonlinear electricity tariffs and the "efficient" column for a counterfactual tariff in which all household consumption and generation are billed at marginal cost. The "solar generation" columns show the annual output of a 1 kW panel for the households who would find it optimal to adopt. The "income" columns show the per capita monthly income for the households who would find it optimal to adopt.

discount rate, we used real annual rates of 2.5, 5, and 10 percent. For the capital cost, installed prices for residential solar declined by between 46 and 85 percent between 2010 and 2020 (IRENA, 2021). There are substantial differences across regions in the installed price of solar panels, with reported costs in California (US$4200 per kW) three times higher than the costs in Spain (US$1400 per kW). We show results for installed system prices between US$500 and US$4000 per kW. We assumed the life of the solar panels is 30 years.

For the existing tariff, the optimal size of the solar system installation will vary across households. It will depend on their electricity consumption, existing tariff, and solar generation potential, as well as the match between their hourly load shape and their hourly solar output. We considered installation sizes between 0.75 kW and 5 kW. For each household, we calculated the panel size that would maximize the net present value of a solar installation for each possible assumption on the discount rate and system price. If the maximized net present value is positive, we classified the household as a potential solar adopter.

For our efficient tariff, the adoption decision does not depend on the installation size. Under this tariff, households pay the marginal cost for their consumption and receive the marginal cost for their excess generation. Because we did not consider possible scale economies in solar panel installation, both installation cost and generation revenue (or the value of avoided consumption) are constant multiples of the installation size. A 2 kW system costs twice as much as a 1 kW system, but the financial benefits would be twice as large.

We report our results as the share of households for whom installing solar panels would be a privately optimal financial decision. This share may not correspond to the actual adoption rates. There may be unobserved barriers to installation, such as financing constraints or site-specific restrictions. Alternatively, there may be household preferences that lead to solar installation even when this is not optimal from a purely financial perspective, perhaps due to conspicuous consumption or concerns about the environment (Bollinger and Gillingham, 2012).

Under the existing electricity tariffs, for a system price of US$2500/kW and a discount rate of 5 percent, 12.3 percent of Colombian households would find it optimal to install solar (Table 5 and Fig. 5). Adoption rates increase at lower system prices. For system prices below US$1000 per kW, optimal adoption rates flatten to 31.3 percent of households. Slightly fewer than 70 percent of households are unable to install solar at any price, either because they rent their dwelling or live in an apartment.[22]

At high system prices, solar adoption under the efficient tariff would be much lower than under the existing tariffs. For a discount rate of 5 percent and a system price of US$3000 per kW, 8.2 percent of households would install solar under the existing tariffs, while no households would adopt under the efficient tariff. The existing tariffs induce solar adoption that is inefficient from the perspective of social welfare. Based on our calculation of the value of electricity generation, including the avoided losses and avoided externalities, the present value of social benefits from a residential solar system in Colombia is less than US$3000 per kW. Paying US$3000 per kW for a system would be welfare-reducing. However, for 8.2 percent of households, the present value of the private benefits of installing solar exceed US$3000 per kW. This level of adoption is an artifact of the distorted tariffs under which the marginal price faced by most households exceeds marginal cost. Social welfare would be improved by implementing a tariff to discourage the inefficient installation of solar at high system prices.

At low system prices, the ranking of adoption under the existing and counterfactual tariffs reverses. For a discount rate of 5 percent and a system price of US$1500 per kW, 22.4 percent of households would install solar for the existing tariffs. For the efficient tariff, 30.5 percent of households would find installation optimal under those assumptions. The higher adoption at low system prices is because the existing tariff undervalues the electricity generation for some households. For many households on the first price tier in Strata 1 and 2, the marginal price avoided by reducing their billed consumption is less than the marginal cost.

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[22] Tables A1 and A2 show the results for real discount rates of 2.5 and 10 percent.

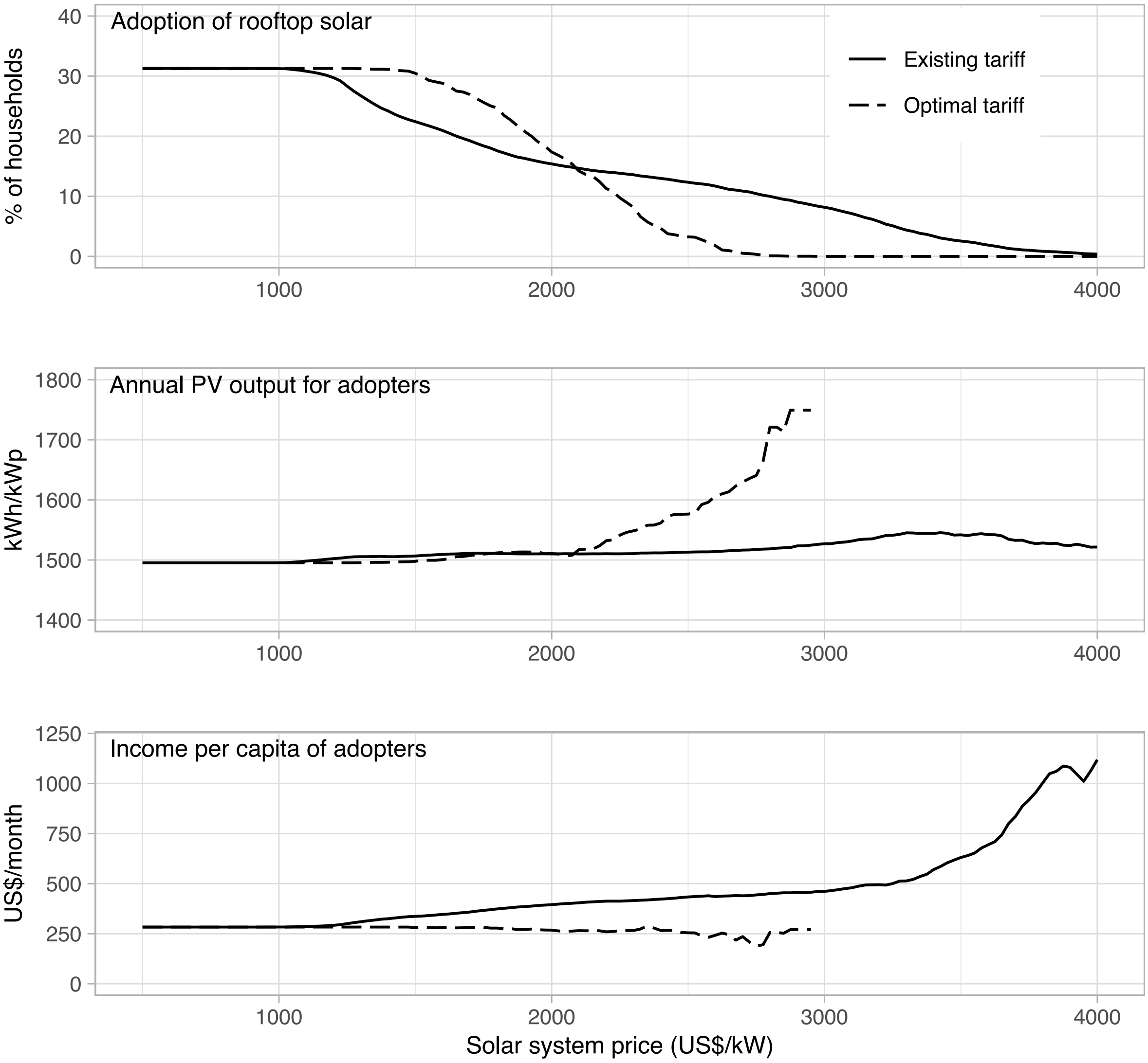

Fig. 5. Characteristics of residential solar adopters in Colombia under existing and efficient tariffs, for different installation prices and a discount rate of 5%. Notes: The top panel shows the share of households for which solar adoption would be privately optimal, under the current tariffs (solid line) and a counterfactual efficient tariff (dashed line), for an annual real discount rate of 5%. Only owner-occupied houses with concrete or brick walls are assumed to be candidates for solar. The adoption calculation assumes the existing retail tariff structure plus the CREG Resolution 30 of 2018 payments for solar generation. The second panel shows the expected solar generation in one year from a 1 kW system for the households for whom adoption would be optimal. The third panel shows the average monthly income per household member for the households for whom adoption would be optimal.

Even for households with solar generation exceeding their monthly consumption, the price they receive for their excess generation is less than the social value of that generation because the wholesale price does not include the avoided losses and externalities.

We illustrate the distorted incentives by showing the characteristics of the potential adopters. Under the efficient tariff, households will install solar for a high price only if they have abundant sunshine and high potential generation. For a system price of US$2500 per kW, the households that would adopt under the efficient tariff have an annual generation of 1.58 MWh per 1 kW of solar panel, compared to a solar resource of 1.50 MWh per 1 kW for adopters at low system prices (Column 5 of Table 5). In contrast, under the existing tariff, the solar potential for adopters is uncorrelated with system prices (middle panel of Fig. 5).

For the efficient tariff, the potential solar generation is the principal determinant of adoption. The income per capita of the adopting households is slightly negatively correlated with the system price (bottom panel of Fig. 5).[23] For the existing tariffs, the households that adopt at high system prices have much higher income per capita. The 0.4 percent of adopters at a price of US$4000 per kW earn more than US$1100 per month, four times higher than the adopters at low prices. High-income households, assigned to Strata 5 and 6, pay a marginal price that far exceeds marginal cost, making it privately optimal to install panels.

The efficient tariff includes a carbon cost based on the greenhouse gas emissions associated with grid-supplied electricity. The carbon price provides an incentive for households to invest in a solar system and reduce their electricity purchases from the grid, which will reduce the generation and emissions from fossil fuel plants. The avoided emissions and generation costs are the social benefit of residential solar installations. By aligning the private and social benefits of solar generation, the efficient electricity tariffs give the correct incentives for households to install solar. For society, the best locations to install rooftop solar are in places with plenty of sunshine, not in affluent neighborhoods with high electricity prices. Moreover, the significantly lower LCOE from utility-scale solar systems relative to rooftop solar systems documented in IRENA (2021) argues for utility-scale systems as the least-cost approach to reducing the carbon content of the electricity sector.

5.2. Adoption of electric stoves

While the existing electricity tariffs in Colombia encourage too many households to install solar, they have the opposite effect on adopting electric appliances. If marginal electricity prices are higher than the social marginal cost, then adoption will be lower than the socially efficient level. Pricing substitute fuels below their social marginal cost exacerbates this problem. To illustrate the effect of price distortions on fuel choices, we study the choice between natural gas and electricity for cooking.

Natural gas is the predominant cooking fuel in Colombia. 65.8 percent of households use natural gas, compared to 23.1 percent using liquified petroleum gas (LPG) and 2.9 percent using electricity.[24] Natural gas is considered a clean, efficient, and “modern” fuel compared to traditional fuels such as charcoal or biomass. Nonetheless, indoor combustion of natural gas may be harmful. Simulation models and air quality measurements show that cooking with natural gas burners without the use of a venting range hood can lead to indoor concentrations of nitrogen dioxide, carbon monoxide, and formaldehyde that exceed air quality standards (Logue et al., 2014; Mullen et al., 2016).

Induction stoves are a cleaner and more efficient alternative to natural gas cookers. Unlike traditional electric stoves that use resistance heating coils, induction stoves use a magnetic field to transfer energy directly into the cookware. In laboratory tests that simulated everyday cooking situations, Livchak et al. (2019) found that induction stoves used 10 percent less energy than traditional electric stoves and 60 percent less energy than natural gas stoves. The induction stoves were also much faster, with water heating times less than half those of traditional electric or natural gas stoves. Induction stoves avoid indoor air pollution from burning natural gas and may reduce greenhouse gas emissions, depending on the marginal fuel used for electricity generation.

Given the private and social benefits of cooking with electricity instead of gas, many jurisdictions have implemented policies to encourage this substitution. More than 40 counties and cities in California have banned natural gas connections in new construction (Roth, 2020). In the Indian state of Himachal Pradesh, 4000 households bought induction stoves as part of a clean cooking energy program (Banerjee et al., 2016). The most ambitious attempt to electrify cooking has been the energy-efficient cooking program in Ecuador, which has a goal of converting more than 80 percent of households from LPG to induction stoves by 2023 (Gould et al., 2018). This program includes promotional campaigns, electricity bill credits, and subsidized loans to buy the stoves.

We provide a financial analysis of the decision to adopt induction stoves for households in Colombia, focusing on the 65.8 percent of households who currently cook with natural gas. Switching from natural gas to electricity for cooking will reduce the natural gas bill and increase the electricity bill. The household gains (or loses) the net change in the two utility bills. We compared the discounted present value of these future savings, over a 15-year horizon, to the induction stove price. If the discounted savings exceed the initial capital cost, adoption would be optimal for the household.

Households will be heterogeneous in their willingness to adopt the new cooking technology because of differences in how much they cook. We capped the natural gas consumption at the 95th percentile of the distribution (44 cubic meters per month) and assumed that all consumption is used for cooking.[25] The maximum consumption is equivalent to running a large gas burner for 3.16 h per day.[26]

Given the estimate of the natural gas used for cooking, we estimated the equivalent electricity consumption for an induction stove. Laboratory measurements for different cooking activities provide an average conversion factor of 4.37 kWh of electricity per

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[23] At high system prices, most adopters are in sunny regions such as the Caribbean coast, where income per capita is lower than the national average.

[24] Natural gas is delivered to homes through a pipeline network. In the early 1990s, Colombia began a program to expand coverage of natural gas. LPG is mostly supplied through cylinders or stationary tanks, although some areas have residential LPG pipelines.

[25] Apart from cooking, the other common residential uses of natural gas are space heating and water heating. In the survey data, only 25.1 percent of natural gas households in Colombia report using water heating. Although the survey did not ask about the fuel used for water heating, the mean natural gas consumption is slightly lower for the households with a water heater, suggesting that electricity is more commonly used for water heating. Space heating with natural gas is uncommon in Colombia. Households in colder highland regions (more than 2000 meters above sea level) have a mean monthly natural gas consumption of 17.4 cubic meters, compared to 20.9 cubic meters in the warm lowland regions (less than 1000 meters above sea level).

[26] Livchak et al. (2019) report a maximum input rate for a gas burner of 17 kBtu per hour. Assuming 30 days in a month, 44 cubic meters per month is 53.7 kBtu per day (EIA, 2021), or 3.16 h at a rate of 17 kBtu per hour.

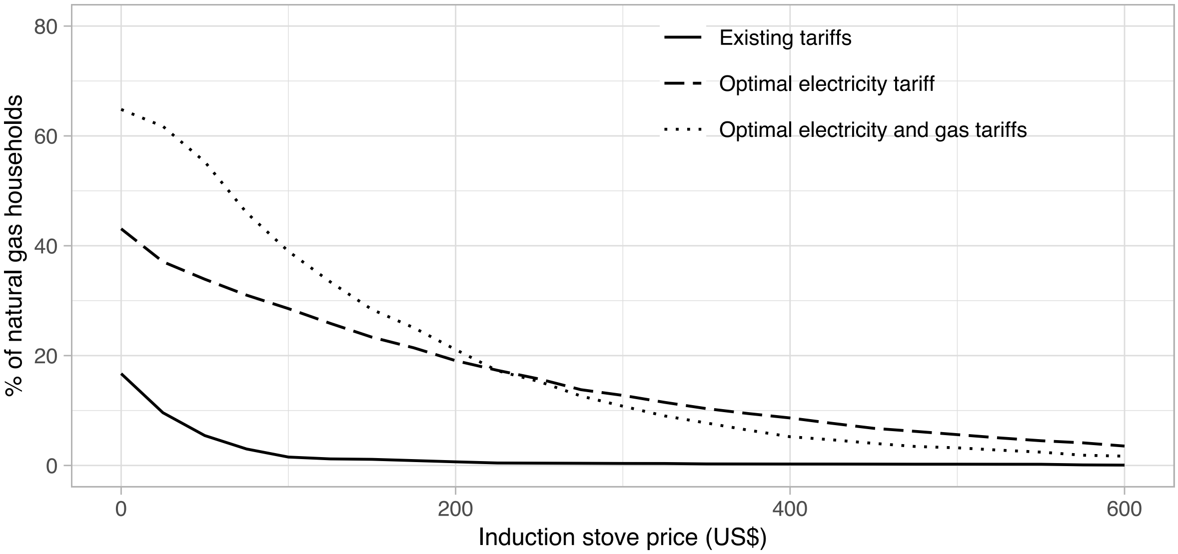

Fig. 6. Optimal adoption of electric stoves in Colombia under existing and efficient tariffs, for different stove prices and a 5% discount rate.
Notes: Each line shows the share of natural-gas-using Colombian households for which adopting an induction stove would be privately optimal, as a function of the stove price, assuming a real annual discount rate of 5 percent. The solid line shows the hypothetical adoption under the existing retail tariffs for electricity and natural gas. The dashed line shows the adoption under an efficient electricity tariff but with the existing natural gas tariffs. Finally, the dotted line shows the adoption under efficient electricity and natural gas tariffs.

cubic meter of natural gas.[27] The mean electricity consumption for induction stove adopters in Colombia would rise from 180 kWh to 280 kWh per month.[28]

Stove prices vary based on the number of burners, so we show the results for a range of different induction stove prices. For the stove replacement program in Ecuador, the price varied from US$150 to US$800, with most households paying about US$500 (Gould et al., 2018). The household's total cost may be higher if upgrades to the internal wiring or grid connection are required. Some adopters may also need to buy new pots and pans because induction stoves only work with ferrous cookware.

Given the existing electricity and natural gas tariffs, the adoption of induction stoves would be optimal for fewer than 1 percent of households for stove prices above US$200 (solid line in Fig. 6). Natural gas users pay an increasing block tariff that varies based on the neighborhood classification, just as for the electricity tariff (Section 2). With increasing block tariffs for electricity and natural gas, the household has a financial incentive to diversify their energy consumption and exploit the low first-tier prices for both fuels. Households switching from natural gas to electricity for cooking would lose the benefit of the low first-tier price for natural gas and possibly pay a high second-tier price for their additional electricity consumption.

Adoption would be higher under an efficient electricity tariff (dashed line in Fig. 6). At a stove price of US$200, it would be optimal for 19.1 percent of households to switch to an induction stove (Table A3). Under the efficient tariff, the household pays the marginal cost for their additional electricity consumption. This tariff eliminates the disincentive for adopting electric appliances created by the high second-tier price in the existing electricity tariff.

Although our focus is on electricity tariff reform, we also calculated the adoption of induction stoves for a scenario with efficient tariffs for electricity and natural gas. We assumed that the efficient price of natural gas is the marginal cost for the supplier, plus the carbon tax of US$46 per ton.[29] For a stove price of US$200, 21.1 percent of households would optimally switch to electricity for cooking. For lower stove prices, there is a larger difference between the two counterfactual tariff scenarios. For a stove price of US$100, 39.0 percent of households would switch under efficient pricing for both electricity and natural gas, compared to 28.6 percent who would switch under efficient tariffs for only electricity.

Under the existing tariff, even if the stoves were free, only 16.7 percent of households with natural gas would find it optimal to switch to the more efficient technology. This result compares to 43.1 percent and 64.8 percent who would optimally choose

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[27] For the most efficient induction stove, Livchak et al. (2019) estimate an electricity consumption of 0.97 kWh per day. They estimate an equivalent natural gas consumption for a gas burner of 8150 Btu, or 0.222 cubic meters, per day, giving a conversion factor of $0.97/0.222 = 4.37$ kWh per cubic meter of natural gas. This estimate is close to the conversion factor of 4.33 kWh per cubic meter used for calibrating the induction stove subsidies in Ecuador.

[28] This calculation assumes marginal cost pricing for electricity and gas tariffs, a stove price of US$200, and a discount rate of 5 percent. Under these assumptions, 21 percent of existing natural gas households would switch to an induction stove.

[29] We estimated the marginal cost of natural gas using the average wholesale cost of natural gas for the utility, plus the average pipeline transportation cost to the household's municipality, scaled up by distribution losses. Wholesale and transportation costs differ based on the source of the natural gas and distance to the natural gas field.

induction stoves under the two efficient tariff scenarios. Adoption would be higher for a stove price of US$200 with efficient tariffs than for free stoves with the existing tariffs. Subsidizing or giving away clean appliances will not necessarily lead to their adoption if utilization costs are distorted.

The above results demonstrate how distorted energy tariffs can lead to inefficient adoption choices for energy-using appliances. The existing tariffs make it optimal for households to choose a slower, less efficient, and more polluting cooking fuel. A similar result holds for other energy services for which households can choose between fossil fuels and electricity. In Appendix E, we show that the existing tariffs encourage the purchase of vehicles using gasoline instead of electricity. In the next section, we describe an efficient electricity tariff that eliminates the short-run and long-run distortions in energy consumption while protecting low-income households from a large increase in their electricity bills.

6. Empirical analysis of alternative retail pricing schemes

In this section, we propose a two-part tariff in which households pay the marginal cost for their consumption plus a fixed charge to recover the shortfall in total costs.[30] The marginal price is set to the quantity-weighted average of the hourly social marginal costs in the month. This differs from the efficient tariff in which the marginal price is equal to the hourly social marginal cost. However, charging a different price each hour would require a meter that records and reports the real-time consumption, and such meters are still uncommon in Colombia. Furthermore, as shown in Section 4.3, we estimate the consumer welfare loss from not using real-time pricing is less than 0.5 percent of expenditure.

Setting a marginal price based on marginal cost will eliminate distortions in the household's electricity consumption decisions. These include both short-term decisions (when to turn on and turn off lights) and long-term decisions (what type of appliance to buy). An efficient tariff will provide the correct incentives to adopt or not adopt new energy technologies such as electric stoves, electric vehicles, or distributed solar.

The problem with marginal cost pricing is that the total revenue would be unlikely to cover the total cost of supplying electricity. Most of the costs for electricity transmission, distribution, and retailing are fixed costs that do not vary based on electricity consumption. The shortfall in fixed cost recovery is recovered through the monthly fixed charge. By definition, the fixed charge does not depend on the electricity consumption of the household, and so it avoids the consumption distortion created by pricing above or below marginal cost.

The simplest method for setting a fixed charge would be to divide the remaining costs evenly between all households. There are two problems with this approach. First, for households with low consumption, the fixed charge may exceed their consumer surplus from using electricity. It would be optimal for such households to disconnect from the grid rather than stay connected and pay the fixed charge. This is likely to be unacceptable for policymakers. Second, from an equity perspective, it might be argued that households who benefit most from having an electricity connection should pay a greater share of the cost of providing the service.

We consider three alternative methods for allocating the fixed charge. The first is based on administrative data about property characteristics available to each distribution utility. This data is used to predict each customer's willingness to pay for grid-supplied electricity at the efficient price using the procedure described in Wolak (2018). Fixed charges are allocated proportionally to the predicted willingness to pay. The second approach uses an existing means test in Colombia for assigning households to subsidized health insurance. Households qualifying for the subsidy would pay a fixed charge of zero. The third approach combines both methods: for the unsubsidized households only, the fixed charges would be allocated proportionally to the predicted willingness to pay.

6.1. Calculation of the revenue requirement

We calculated the revenue required to recover fixed costs for each electricity distributor. We assumed that the existing residential base tariff recovers all costs and provides a return on invested capital, given the existing level of consumption.[31] The total revenue requirement is the base tariff multiplied by total consumption. Variable costs are the wholesale price of electricity, plus reconciliation payments and losses, multiplied by total consumption. The fixed cost requirement is the difference between the total revenue requirement and the variable costs.

In our proposed two-part tariff, there are three sources of revenue to cover the fixed costs of each utility. First, the marginal price in the efficient tariff includes the cost of carbon. Each distribution utility can keep this carbon tax revenue. Second, the subsidy transfers incorporated into the existing tariffs remain fixed. These transfers include the contributions paid by the non-residential users and the government top-up of the subsidy shortfall. Finally, any remaining cost shortfall is recovered through a fixed charge on household electricity bills. Figure A5 shows the breakdown of the revenue requirement, per household per month, by electricity

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[30] We assumed that revenue can be raised in a non-distortionary manner through a fixed charge that may vary across households. This is a reasonable assumption for utility tariffs, which often include a fixed monthly charge. If it were not possible to use fixed charges, then consumption distortions would be inevitable. In that case, the least distortionary approach for raising revenue would set the variable charge for each household type in inverse proportion to its demand elasticity (Ramsey, 1927). As McRae (2015) demonstrates, low-income households in Colombia typically have the most price-inelastic electricity demand, so Ramsey pricing could result in setting the highest prices for the lowest-income households.

[31] Implicit in the calculation of the base tariff is an allocation of utility fixed costs between residential and non-residential users. This allocation is also held constant for our analysis.

distributor. For three distribution utilities, the fixed charge is negative because the existing subsidies for these firms already cover most or all of the revenue requirement. The maximum fixed charge is slightly more than US$4 per household per month.

We did not consider an alternative tariff in which the subsidy transfers for electricity service are eliminated. The total subsidy transfers from the non-residential users and the government are nearly US$70 million per month, or more than US$5 per household per month (Table 1). The welfare gains from efficient pricing are not large enough to compensate for the loss of this revenue. Nonetheless, the resources currently allocated to electricity subsidies could be used for alternative social transfer programs or tax reductions. The net distributional effect would depend on the design of these programs.

6.2. Methodologies for targeting fixed charges

Shifting to an efficient two-part tariff for electricity in Colombia will likely require a mechanism to vary the fixed charge across households. Ideally, differences in the fixed charge would correspond to differences in the willingness to pay for electricity. The practical challenge is that the fixed charge cannot be based on the observed consumption of a household—by definition, it would no longer be a fixed charge. In this section, we discuss a proxy for the willingness to pay that is not based on contemporaneous consumption.

Our preferred targeting approach would set the fixed charge proportional to the customer's willingness to pay for grid-supplied electricity at the efficient price. Wolak (2018) demonstrates that this procedure can be implemented using a regression of squared electricity consumption on dwelling characteristics, then using the estimated coefficients to predict squared consumption. The share of fixed costs allocated to an individual household would be its predicted willingness to pay to consume electricity, divided by the sum of predicted willingness to pay for all households in the distribution territory.

Wolak (2018) motivates the use of predicted squared consumption as a measure of the willingness to pay based on a model that assumes households have linear hourly demand curves for electricity with the same slope but intercepts that vary hourly. The expected annual consumer surplus from electricity consumption will be a constant multiple of the expected value of squared consumption. Allocating fixed costs based on predicted squared consumption therefore approximates an allocation based on willingness to pay to consume electricity at the efficient marginal price. Appendix F provides a graphical illustration of this result.

Our approach is particularly appealing from a theoretical perspective. Proxy means tests are commonly used for targeting social programs (Hanna and Olken, 2018). However, the weights on different household characteristics and the qualification thresholds may be set arbitrarily. For our application, the weights are determined by a regression of squared electricity consumption on household characteristics. The predicted values can be directly interpreted as a measure of the household's willingness to pay to consume electricity.

A methodology using dwelling characteristics to predict willingness to pay is feasible to implement in practice. The model inputs include information that is available in the national cadastral database (Figure A6). For each land parcel, the database includes information on the building footprint, number of rooms, number of bathrooms, floor area, and a measure of the quality of construction. Distribution utilities are required to include the cadastral identifiers in their customer databases. This would facilitate matching the consumption data to the dwelling characteristics.

The proposed allocation mechanism is related to a new methodology adopted by the national statistical agency DANE for the classification of households into six strata. The stratification used to be based on observations of neighborhood characteristics during enumerator site visits. The refined approach uses cadastral data to classify the neighborhoods. Our proposed methodology avoids the intermediate step of grouping households into six coarse strata. This step loses valuable information in the cadastral data that can be used to predict each household's willingness to pay to consume electricity.

A final attractive feature of our methodology is that the predicted squared consumption may be negative. In that case, the fixed charge assigned to the household would be negative. This result may occur for households with observable characteristics that are correlated with extremely low electricity consumption. Such households have a low willingness to pay for electricity—in which case, assigning a zero or negative fixed charge is appropriate.

We present a second methodology for allocating fixed charges, using the classification of households under the government-subsidized health insurance program. Eligibility for government-subsidized health insurance in Colombia, as well as eligibility for other programs including housing subsidies, educational scholarships, and school lunches, are determined by a proxy means test known as SISBEN.[32] We considered two tariffs under which the fixed monthly charge is zero for households who qualify for the health insurance subsidy. For one tariff, the fixed charge is equal for all unsubsidized households. For the other tariff, the fixed charge for the unsubsidized households is set proportional to their predicted willingness to pay to consume electricity at marginal cost.

To compare the different tariffs, we calculated the change in consumer surplus from switching from the existing tariff to the alternative tariff. We calibrated a linear demand curve for each household to match existing prices and consumption, given a price elasticity of demand of −0.30. For the existing tariffs, consumer surplus was calculated based on the current marginal price faced by the household, plus the value of any inframarginal subsidies. For the new tariffs, consumer surplus was calculated based on the new variable charge and corresponding counterfactual consumption, less the amount of the fixed charge. The benchmark for our analysis is a tariff that sets the same fixed charge for all households served by a distribution utility.

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[32] Miller et al. (2013) study the effectiveness of the health subsidy program at reducing risk, enhancing preventive care, and improving health outcomes. Camacho and Conover (2011) study strategic manipulation of the SISBEN eligibility formula by local politicians. The SISBEN interviews do not cover the entire population. Rich households who almost certainly would not qualify, including households living in high strata neighborhoods, typically do not participate.

Table 6
Summary of results for alternative mechanisms to allocate fixed charges.

Allocation mechanism	$CS_1 - CS_0$	$\mathrm{I}(CS_1 < 0)$	$\mathrm{I}(CS_1 < CS_0)$
Equal fixed charges	0.84	0.98	62.03
Use predicted WTP	0.84	0.41	58.47
Zero fixed charges for SISBEN	0.84	1.07	59.37
Zero SISBEN + predicted WTP	0.84	0.45	56.34

Notes: Each row shows the summary results for a fixed charge allocation mechanism, corresponding to the distributional results shown in Fig. 7. The first column shows the mean change in consumer surplus across all households for that mechanism. The second column shows the percentage of households under that mechanism with negative consumer surplus, who may find it optimal to disconnect from the grid. The final column shows the percentage of households with a lower consumer surplus under the mechanism than under the current tariff.

We simulated the tariff based on predicted willingness to pay using dwelling information from the household survey. We regressed the squared electricity consumption of each household on the dwelling type, the number of rooms and bedrooms, the wall and floor materials, the type of bathroom and kitchen, the availability of services (including water, wastewater, telephone, internet, and cable TV), and a quadratic in rental prices.[33] The regression included neighborhood fixed effects. We ran the analysis separately by state to allow for regional heterogeneity in the determinants of electricity consumption. From these regressions, we predicted each household's willingness to pay to consume electricity at marginal cost and used this predicted value to calculate the share of fixed costs.

Survey respondents reported whether they have private health insurance through their employers or whether they qualify for subsidized insurance. For the tariff based on the health insurance subsidy, we assumed that households received the subsidy if they had at least one member who qualifies for subsidized insurance. These households pay a zero fixed charge under the third and fourth tariff alternatives that we consider.

6.3. Results for targeted fixed charges

The first bar in Fig. 7 shows the effect by income decile of a uniform fixed charge within each distribution utility. On average, households would be better off by US$0.84 per household per month. However, this benefit is far from evenly distributed. Households in the bottom half of the income distribution are worse off than under the current tariffs, by more than US$2 per household per month for deciles 1 and 2. Most of the benefits of the new tariff would accrue to households in the top four deciles. Households in the highest income decile are particularly better off, by more than US$8 per household per month.

The second tariff presented in Fig. 7 allocates the fixed charges based on each household's share of predicted willingness to pay to consume electricity at the efficient marginal price. Compared to a tariff with uniform fixed charges, this methodology reduces the gain in consumer surplus for high-income households and reduces the loss in consumer surplus for low-income households. However, households in the bottom half of the income distribution are still worse off on average compared to the existing tariff.

The third and fourth tariffs in Fig. 7 show the result of setting fixed charges to zero for the households receiving subsidized health insurance. Households in deciles 4 to 10 are at least slightly better off on average under the fourth tariff. High-income households are still better off, but not by as much as when fixed costs are divided equally for everyone. The fourth tariff, combining the allocation mechanisms in the second and third tariffs, gives the most uniform distributional outcome.

We consider alternative metrics for evaluating the targeting mechanisms in Table 6. Each row in the table represents one of the four alternative tariffs. The first column shows the mean change in consumer surplus for all households. This is the same for all tariffs.

The second column of the table shows the percentage of households who would receive a negative surplus from having an electricity connection after the change to the economically efficient tariff. Households with a negative surplus would prefer to disconnect from the grid rather than pay for a connection they do not value. The energy regulator may wish to avoid a tariff under which significant numbers of electricity consumers would want to disconnect. For the existing average cost tariff, with no fixed charge, every household in Colombia receives a positive consumer surplus from their electricity connection.

It is difficult to have an efficient tariff that does not leave any household with a negative surplus. However, the allocation mechanism that performs best is the assignment of fixed charges based on the share of predicted willingness to pay (row 2). This approach does well because of the explicit link between the fixed charge and the expectation of the household's willingness to pay for electricity. Tying the fixed charges to the health insurance subsidies performs badly on this metric (row 3). There are nearly three times as many households who would want to disconnect than under the predicted willingness to pay mechanism. This is because there are households with low willingness to pay for electricity that do not qualify for the health insurance subsidies, who would be allocated a larger share of fixed costs than under the system of equal fixed charges for everyone (row 1).

The third column of results in Table 6 shows the percentage of households who would be worse off under the new tariff than under the existing tariff. The fourth tariff performs best on this metric. Even though the new tariffs create an increase in mean consumer

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[33] The rental price is a proxy for the value of the dwelling. In the survey, renters were asked to report their monthly rent. Other respondents were asked to estimate the monthly rent for the dwelling.

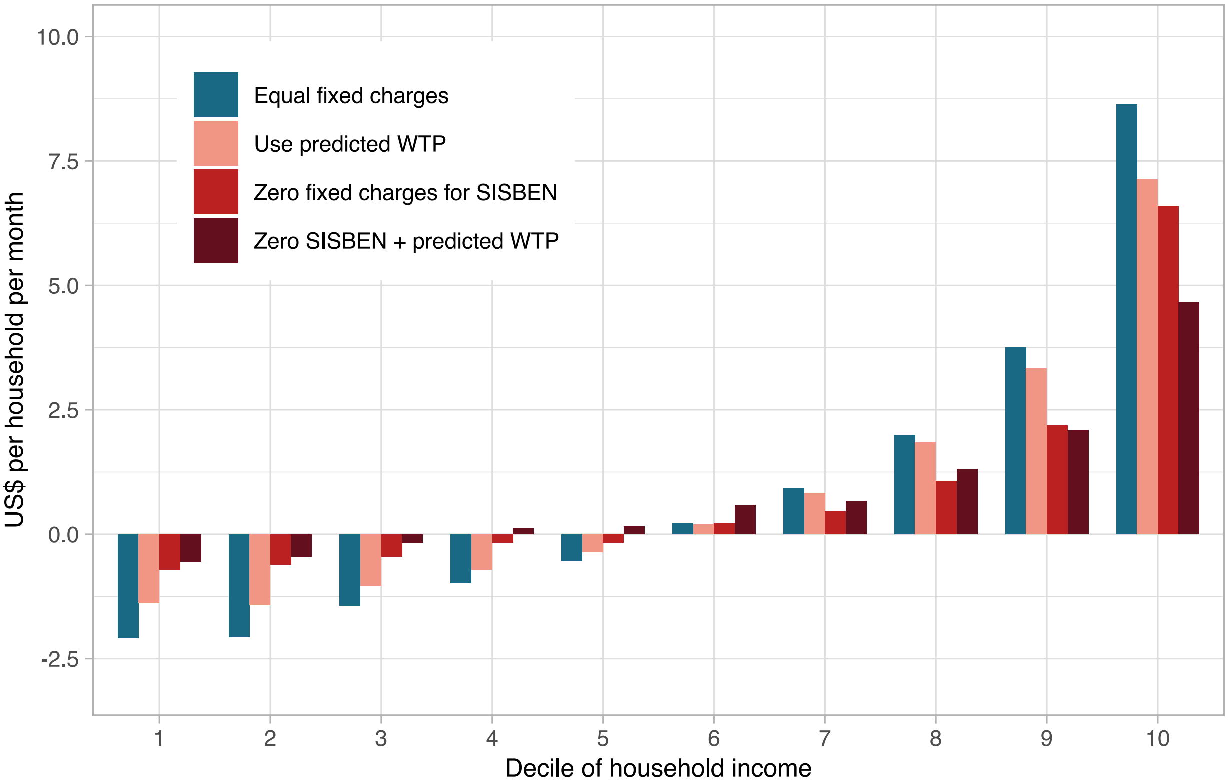

Fig. 7. Distributional effects of alternative mechanisms for fixed charge allocation.
Notes: Each bar corresponds to an income decile in the Colombian population (1 = lowest, 10 = highest). The height of the bar is the mean change in consumer surplus from a change from the current tariff to a counterfactual tariff with the variable charge equal to social marginal cost. The results for four mechanisms for allocating the remaining fixed costs are shown: (i) setting uniform fixed charges for all households served by a utility, (ii) setting fixed charges proportional to the predicted willingness to pay to consume electricity at marginal cost, (iii) setting fixed charges equal to zero for households with subsidized health insurance, and equal across the remaining households within a utility, and (iv) setting fixed charges to zero for the households with subsidized health insurance and, for the remaining households, proportional to the predicted willingness to pay. Consumer surplus and the change in consumption under the new tariff are calculated under an assumption of linear demand and a price elasticity of −0.30.

surplus, the majority of households would be worse off for every allocation mechanism. This result is a consequence of the skewed distribution of electricity consumption (Fig. 1). Under average cost pricing, a small number of households with high electricity consumption pay a disproportionate share of fixed costs. Reallocating these costs across the entire consumption distribution will inevitably leave many households worse off.

Our results highlight the political challenges for the transition to an efficient pricing mechanism for electricity. The current tariff structure is particularly favorable for low-income households with low electricity consumption, who pay no fixed charges and a variable charge set below the marginal cost of providing the service. Their price per kilowatt-hour will necessarily rise under the efficient tariff. This means that even if they do not pay a fixed charge under the new tariff, they will be worse off because of the higher price per kilowatt-hour. The only way for the low-income households to stay equally well off under the efficient tariff will be to set a negative fixed charge, which amounts to an allocation of “free” electricity consumption at marginal cost.

Conversely, high-income households will benefit greatly from a transition to an efficient tariff. Their electricity consumption is high, and they pay a price per kilowatt-hour that is many times higher than the marginal cost. The reduction in their variable charge will leave them better off, even if they have to pay a relatively high fixed charge with the new tariff.

Our results also illustrate the welfare effects for low-income households of carbon pricing. Under our assumption of a carbon tax of US$46 per ton, a large share of the fixed cost recovery for electricity distributors is provided by the carbon tax revenue (Figure A5). Because the total revenue from fixed charges is relatively low, varying the fixed charges based on our estimate of the willingness to pay of households is insufficient to compensate low-income households for the transition to efficient retail prices.[34]

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[34] We illustrate this result by replicating Fig. 7 and Table 6 for a carbon tax of US$23 per ton (Figure A7 and Table A4). With the lower carbon price, a higher share of revenue is collected from fixed charges. Our fourth mechanism for allocating the fixed charges based on the combination of zero fixed charges for households receiving subsidies for health insurance and our predicted willingness to pay to consume electricity at the efficient marginal price for the remaining households leaves every decile better off on average, with the largest average gain for households in the lowest four deciles.

These adverse distributional effects show that higher carbon prices may make the renewable energy transition more difficult to achieve, especially in developing countries.

7. Conclusion

Achieving the climate goals outlined in Rogelj et al. (2018) will require a transformation of the existing energy systems in every country. The potential benefits of this transition are greatest in developing countries, where energy demand growth is highest, and there are more opportunities for “leapfrogging” to low-carbon technologies.

In this paper, we showed that the residential electricity prices in Colombia create both short-run and long-run distortions in household capital investment and energy-consuming decisions. The tariff distortions are increasingly salient because of new technologies for the production and consumption of electricity, such as residential rooftop solar, electric stoves, and electric vehicles. The still-nascent market for these technologies makes this a propitious time to reevaluate the electricity tariff structure.

We propose a potential path for improving the efficiency of electricity pricing in Colombia. Reducing the price per kilowatt-hour and introducing fixed charges will enhance the economic efficiency of the tariffs. In a developing country, where there is substantial heterogeneity in income and electricity consumption, setting the same fixed charge for all households may leave those with low electricity consumption worse off than they would be with no connection at all. Our proposal to vary the fixed charge by household, based on its estimated willingness to pay to consume electricity at marginal cost, would considerably reduce this concern. It is also feasible to implement given the information available to electricity suppliers in Colombia.

Our proposed tariff reforms would have different effects on the rooftop solar and electric stove markets in Colombia. Lower prices for electricity consumption, especially for high-income households, would encourage the adoption of clean technologies such as electric stoves. However, we also showed that switching to an efficient tariff would lead to a reduction in residential solar adoption at high system prices. This is a feature, not a bug, of the proposed tariff reform. Social welfare is not enhanced by households who install solar systems because of the high prices they pay under a distortionary electricity tariff. The social value of the electricity produced by their systems is less than the cost of installation, even after accounting for the avoided externalities from conventional electricity generation. Moreover, solar energy can be obtained at a lower LCOE from utility-scale generation units than from rooftop systems.

Our results on the distributional effects of the proposed tariff reform suggest that it will not be possible to make everyone better off under the new tariffs. This is an inevitable consequence of the inefficiencies in the existing tariff, in which payments by some households do not even cover the marginal cost of supplying electricity. Keeping the current tariffs will not make this problem disappear. It will get worse over time.

The problems with the existing tariffs and the benefits of our proposed reform apply to virtually all industrialized and developing countries. Our tariff design provides households with the incentives for the eventual electrification of energy services that are currently provided by fossil fuels. Our methodology for allocating fixed charges based on the estimated willingness to pay to purchase electricity at marginal cost avoids the potential legal and political barriers of means-tested fixed charges. It is feasible for both developing and industrialized countries. In addition to its local economic, environmental, and health benefits, the proposed reform will contribute to the global goal of achieving net-zero carbon emissions.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2021.102541.

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