Why are Connection Charges So High? An Analysis of the Electricity Sector in Sub-Saharan Africa*

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High electricity connection charges and low access rates are common in Sub-Saharan Africa. We estimate a model of household and utility behavior, in which households choose their fuel source and consumption quantity, and profit-maximizing utilities set connection charges. Low regulated tariffs and low household consumption make it difficult for utilities to recover their costs. For each possible tariff, we compute the optimal connection charge for the utility, and show that higher tariffs are associated with lower connection charges and higher electrification rates. Nevertheless, limited willingness to pay for electricity leads to equilibrium electrification rates below 100 percent.

JEL: L51, L94, O12, O55

Keywords: connection charges, electricity access, Sub-Saharan Africa, Uganda

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1 Introduction

Electrification rates in Sub-Saharan Africa are the lowest of any region in the world. In 2020, 48.4 percent of the population had access to electricity, compared to 22.8 percent in 1990.[1] Lack of electricity can stunt economic development through various channels including education, labor supply, and productivity (Dinkelman, 2011; Fisher-Vanden et al., 2015; Allcott et al., 2016; Chakravorty et al., 2016).

Many factors contribute to this highly complex problem of limited access to electricity. This paper is concerned about one of these factors, namely electricity connection charges.[2] These are the fixed upfront amount that new customers pay to connect to an existing distribution network. In many African countries, electricity connection charges are very high, both relative to local incomes and relative to connection charges in other parts of the world. Golumbeanu and Barnes (2013) argue that high electricity connection charges may be the most significant obstacle to improving electricity access in the Sub-Saharan Africa region.

In this paper, we develop a model of household and distribution utility behavior to describe how high connection charges and low access rates can arise from regulated electricity tariffs that are set too low.[3] Wholesale costs of generating and supplying electricity in many parts of Africa are high. However, in many countries, regulated tariffs are set below a level that would allow utility firms to recover these costs (Trimble et al., 2016). The potential losses from connecting additional customers make it optimal for distribution utilities to set high connection charges. These high charges reduce the demand for connections, screen customers so that only those with high willingness to pay choose to connect, and recover future losses from the customers who do connect.

Our analysis requires the estimation of a household-level model of the joint demand for electricity and electricity connections. Households are assumed to choose between several alternatives for their primary fuel source, including kerosene, grid electricity, and solar.[4] This choice will depend on, among other factors, the capital cost of the fuel

1. World Bank Global Electrification Database, http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS.

2. Other important factors include low households' willingness to pay for electricity service at market prices, high costs of electrification, and inefficient and dysfunctional utilities (Kojima et al., 2016; Trimble et al., 2016).

3. Other potential explanations for these high charges include geographical challenges for network construction, inefficient procurement practices, and excessive stringency of technical standards (Golumbeanu and Barnes, 2013). As we demonstrate below, these explanations are not inconsistent with our framework. Rather they tend to exacerbate the problem we discuss.

4. In practice, many households use multiple energy sources for different purposes, such as charcoal for cooking and kerosene for lighting. Because households rarely cook or heat with electricity in our setting, we focus on the choice of energy source for lighting.

source, the fuel price and availability, and the characteristics of the household. We then estimate a panel data model for the household's electricity consumption, accounting for the sample selection bias due to only observing consumption for the households who choose to connect.

We estimate our model using data from Uganda. The electricity industry in Uganda was restructured starting in 1999, and the reform process has been one of the most advanced in Africa. It included the vertical separation and partial privatization of the incumbent utility (Mawejje et al., 2013). The system operator, Uganda Electricity Transmission Company Limited (UETCL), is responsible for electricity purchases from independent generators. Electricity distributors, including the largest distribution utility Umeme, pay a regulated price to buy electricity from UETCL. This feature of the restructured industry is useful for our analysis. The regulated wholesale price makes the cost for a distribution utility of adding a customer more transparent than it would be in the case of a vertically-integrated firm.

The Electricity Regulatory Authority in Uganda sets tariffs using a rate-of-return methodology (Electricity Regulatory Authority, 2006).[5] The revenue requirement for each firm is the sum of operating and maintenance costs, lease costs, and costs related to capital investment, including an allowed rate of return on invested capital. The revenue requirement is split by customer category and divided by electricity volumes to calculate the unit price (Pöyry Management Consulting, 2012). Under rate-of-return regulation, firms have an incentive to keep the connection and fixed charges low to encourage new connections and increase their rate base (Averch and Johnson, 1962; Davis and Muehlegger, 2010). However, this result may not hold if regulators cannot credibly commit to setting future tariffs that allow for recovery of past capital investment (Laffont and Tirole, 1986). For example, in Uganda, the president has directly intervened in favor of particular energy projects, overriding existing contracts. This type of interference has undermined investor confidence (Whitley and Tumushabe, 2014, p.25). Another issue is that bureaucratic red tape may increase the cost of projects but not be recoverable through additions to the rate base.

The primary data source for our analysis is the Uganda National Panel Survey. We use data from the seven waves of this survey, from 2009–10 until 2019–20. Our sample period captures a remarkable energy transition in Uganda. At the start of our sample, more than 80 percent of households used kerosene lamps for lighting. This proportion had declined to

5. The regulator reviews the rate-of-return tariffs annually for each firm. There is a quarterly adjustment to allow for pass-through of changes in fuel prices, inflation, and exchange rates.

15 percent by 2020, as modern energy sources (electricity and solar) replaced unimproved sources. The survey includes a module on household energy use that allows us to observe these changes over time within a household. We use GIS data on the distribution network to construct measures of the availability and density of the electricity grid. Monthly price data for energy commodities is from the Uganda Bureau of Statistics and (for electricity) the Electricity Regulatory Authority. Distribution utility financial data is always from the electricity regulator.

Our primary motivation for estimating the demand model is to analyze the incentives faced by the distribution utility. For a utility charging a high regulated price, sufficient to cover variable costs, each additional connected household will make a positive contribution to profits. These profits create an incentive for the utility to reduce its connection charge so that more households wish to connect. The utility trades the lost revenue from a lower upfront connection charge, against the higher future profits from having more customers. This description matches the current setting in Uganda.

An alternative scenario is that the utility charges a low regulated price that is insufficient to cover variable costs. This lower price means that each connected customer has a higher electricity consumption. However, the utility loses money on each customer that connects, creating an incentive to set a high upfront connection charge to discourage new connections. This analysis describes the electricity sector for several countries in Sub-Saharan Africa and explains the observation of low connection rates combined with high connection charges.

Despite our choice of setting, we should emphasize that the regulatory distortion created by low retail prices is not an issue in Uganda. Instead, we will show that the regulated price in Uganda is sufficient to recover the costs of supplying electricity, and given this regulated price, the connection charge set by Umeme is close to optimal. Along with the Seychelles, Uganda is one of only two countries in Sub-Saharan Africa that Trimble et al. (2016) describe as having a financially viable electricity sector. Nonetheless, with our joint model of households and the distribution utility, we can undertake counterfactual analyses using different prices, to explore the relationship between regulated tariffs, connection charges, and access rates. Furthermore, despite the reforms, electricity access rates in Uganda are low, although increasing. We can use our model to explore the other demand-side and supply-side factors that have constrained connection rates.

The analysis in this paper is closely related to the theoretical literature on optimal two-part tariffs for regulated monopolies. Feldstein (1972) studies the trade-off between a fixed charge and a marginal price per unit for a regulated monopoly, assuming all households pay the same prices, in a setting in which households have different marginal utilities of income. However, he assumes that all households are connected and must pay the fixed charge. Sherman and Visscher (1982) study the more general problem in which households can choose whether or not to connect. The monopolist can choose to reduce the connection charge (and add more customers) or reduce the marginal price (and increase the consumption per household).[6] In that case, the optimal two-part tariff depends on the relative demand elasticities.

There is a growing literature that studies the causes and effects of the lack of electricity provision in many parts of the developing world. Lee et al. (2020) induce experimental variation in connection charges in Kenya to estimate the demand for an electricity connection. They find that the consumer surplus from a connection is less than their estimate of the cost of a new connection. This result suggests that programs to increase electrification may be welfare-reducing.

Our study differs in many respects from the analysis in Lee et al. (2020). In our model, the value of electrification is the future stream of energy services that the household receives from the connection. Changing the retail price of electricity will change the benefit that the household derives from these future services. However, changing the retail price will also change the profitability for the distribution utility of providing a connection. Unlike in Lee et al. (2020), we explicitly account for the role of these future costs and future benefits, for both the utility and the household, in the decision to provide (or obtain) an electricity connection. Our approach also makes explicit the role of an industry regulator in setting retail prices and changing the incentives for both the utility and the household.

Our analysis is closely related to the model in Burgess et al. (2020) and their empirical findings for Bihar, India. In that paper, the authors show how below-cost electricity tariffs lead to the rationing of the electricity consumption of connected households by way of rolling blackouts. Our paper also shows how below-cost tariffs can lead to a form of rationing, but through higher connection charges that limit the number of connected households.

There are numerous socioeconomic, engineering, and political challenges that contribute to the low rate of electrification in Sub-Saharan Africa. As with any modeling exercise, our analysis omits many of these factors. Instead, we focus on a previously little-remarked problem: the role of regulated tariffs set below cost-recovery levels and

6. In our analysis, we consider a simpler case, where an external regulator fixes the marginal price, and the only choice for the regulated utility is the level of the connection charge.

the disincentive these create for distribution utilities to connect new customers.[7] We believe that a narrow focus on "high connection charges" may lead to a misdiagnosis of the problem. If connection charges are high because distribution utilities wish to discourage unprofitable connections, then providing connection subsidies may result in the utilities using non-price barriers to connection instead. These might include, for example, reducing the reliability of electricity supply, or increasing the wait time for a connection. The latter has been a recent problem in Uganda following the implementation of a program to heavily subsidize residential connections.

For the remainder of the paper, Section 2 describes the data used for the analysis, Section 3 sets out our model of households and firms, and Section 4 presents our empirical findings. Finally, Section 5 discusses the implications of our results.

2 Data

The data sets compiled for this analysis including household characteristics and energy consumption from seven waves of the Uganda National Panel Survey (UNPS), geographical data on the electricity transmission and distribution networks, monthly energy prices by region, and operating and financial data for the electricity distribution utilities.

2.1 Household survey data

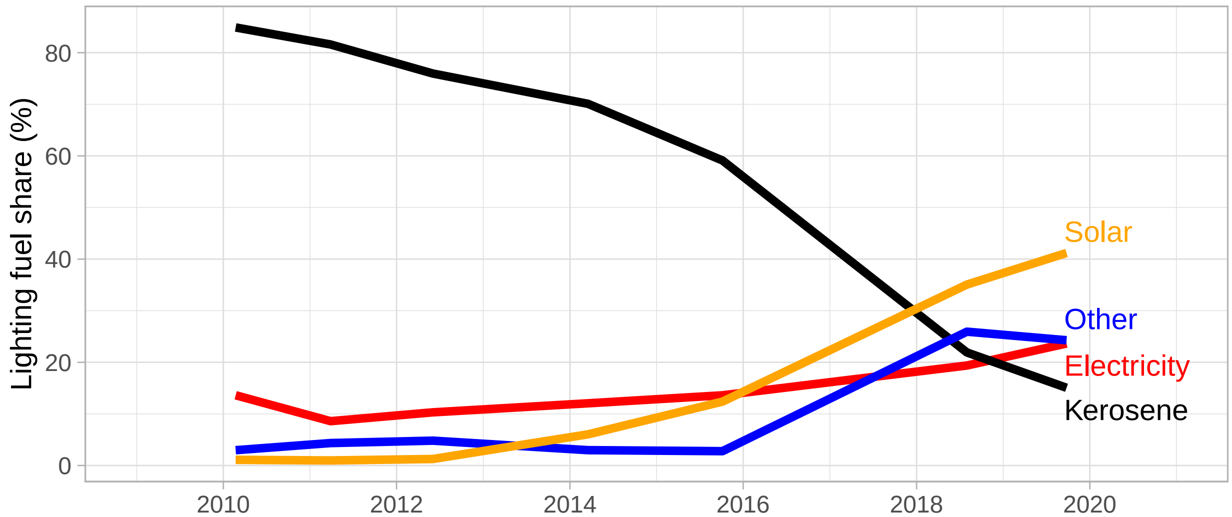
The Uganda National Panel Survey (UNPS) is a household panel survey that began in 2009. We use seven waves of the data from 2009–20 until 2019–20. There are approximately 3000 household observations in each year of the data. These include 1170 households that are followed through all seven survey waves. Another part of the panel was refreshed in 2013.

An appealing aspect of the UNPS for our analysis is the level of detail in the energy use module.[8] The survey recorded the consumption quantity and the total amount paid for each energy commodity. The survey also recorded the energy sources used for the three energy services of lighting, cooking, and heating. For our analysis, we focus on the energy

7. This analysis has parallels with the setting described by McRae (2015). In Colombia, the regulator sets high subsidy reimbursement rates for informal settlements, creating a disincentive for distribution utilities to upgrade the quality of the infrastructure serving these areas. This result holds even if the upgrade could convert non-paying households to paying customers.

8. We examined the energy questions contained in 17 Living Standards Measurement Surveys in Sub-Saharan Africa. The UNPS is the most complete of these, with 33 out of 41 possible energy-related questions.

Figure 1: Energy sources used for lighting, 2009–2019



Notes: Data from seven waves of the Uganda National Panel Survey (2009 to 2019). Totals may add up to more than 100% because households could report more than one energy source for lighting. Most observations in the "other" category are torches or firewood.

source used for lighting, as this is the service that is most likely to be replaced by electricity after the household has a grid connection.

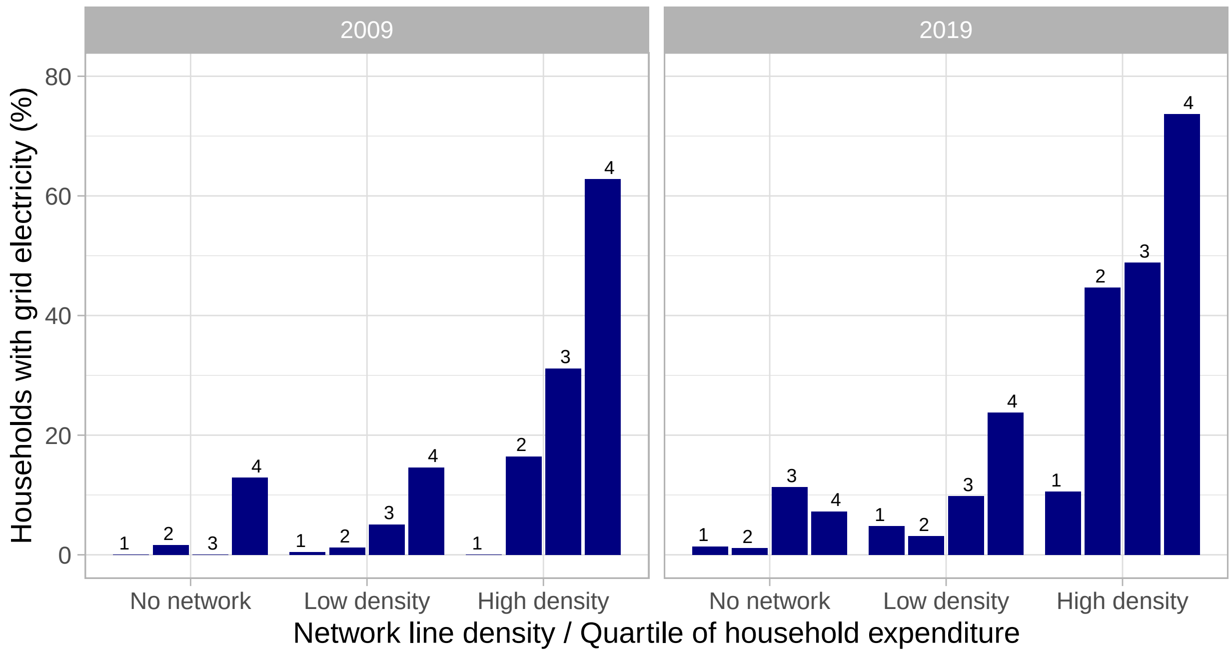
The period covered by our survey data incorporates a remarkable transition away from kerosene lighting to lighting provided by modern energy sources (Figure 1). In 2010, more than 80 percent of households reported using kerosene lamps as their source of lighting. This share declined to 15 percent by 2019. The largest increase in lighting came from small solar kits, whose share increased from 1 percent to 41 percent. The use of electricity for lighting increased from 14 percent to 24 percent of households.

2.2 Electricity coverage

The decision by a household to obtain an electricity connection depends on the availability of the electricity grid in the household's community. Extending the grid to a new area would be prohibitively expensive for a single household. We develop several complementary measures of grid availability for each household in the survey data.

We have GIS data on the transmission and distribution network in Uganda as of 2016 (Energy Sector GIS Working Group Uganda, 2020). We combine this data with a map of the administrative boundaries to create a parish-level measure of grid availability. For each parish, we calculate the length and density (kilometers of lines per square kilometer)

Figure 2: Share of households with electricity connections, by expenditure quartile and network density, 2009 and 2019



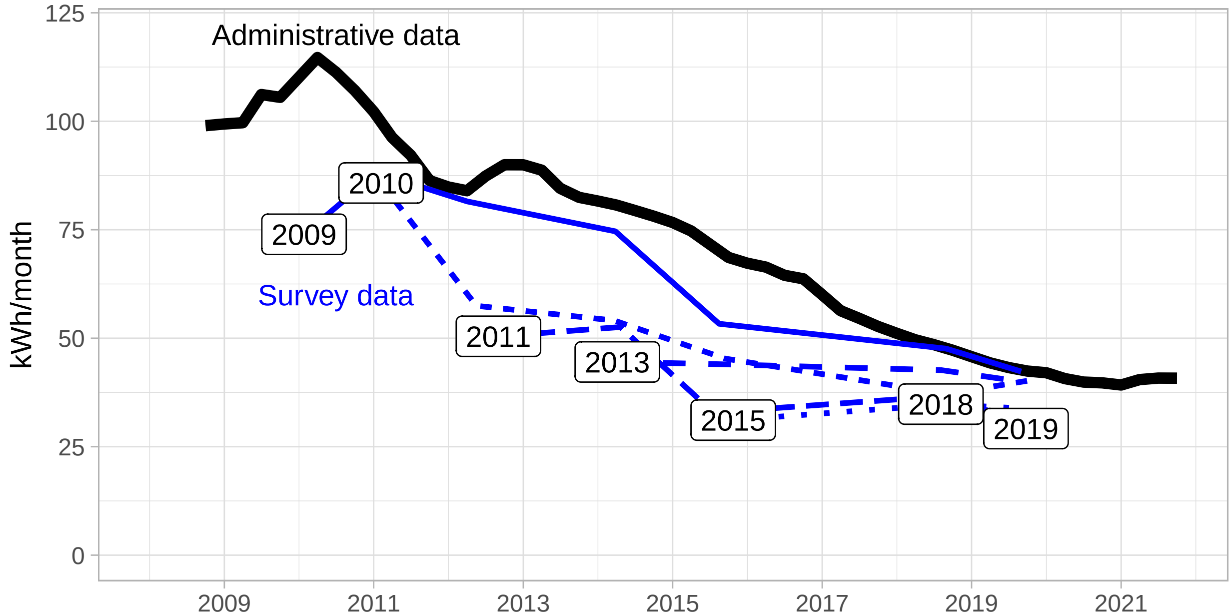
of the grid. For parishes without any distribution lines, we calculate the distance to the nearest line.

For every household expenditure quartile, the probability of having an electricity connection is greatest in parishes with the greatest density of lines, measured as being in the upper half of the line density distribution (Figure 2). These are typically parishes located in urban areas. In 2019, nearly three quarters of households in the highest expenditure quartile and living in areas with a high density of distribution lines had a grid electricity connection. This compares to less than a quarter of households in the highest expenditure quartile living in areas with a low density of lines.

Between 2009 and 2019, the share of connected households increased across all parts of the expenditure distribution. The largest increase occurred for households in the second and third expenditure quartiles. In high-density areas, the share with a connection increased from around 20 to 30 percent to nearly 50 percent. The increase was smaller for households in the lowest expenditure quartile and for households in areas with a low density of lines. In spite of the increase in connection rates, there are still many households close to the network without a connection.[9]

9. The finding that many households close to the grid are unconnected matches the findings of Lee et al. (2016). They

Figure 3: Monthly electricity consumption per connected household: comparison of administrative and panel survey data

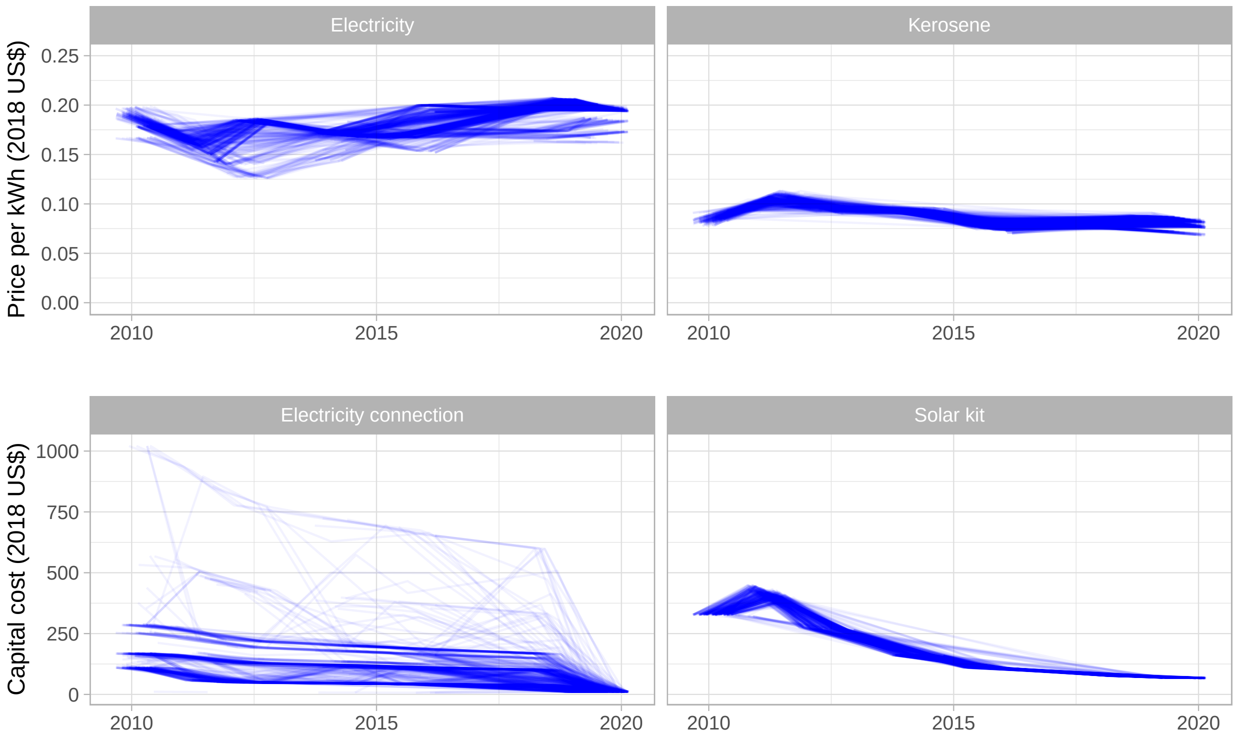


We can use the household survey data to provide insight into the electricity consumption patterns of the newly connected households (Figure 3). Each line labelled with a year on the figure shows the mean electricity consumption for surveyed households that first obtained an electricity connection in that year. Only households that remain in the dataset until 2019 are included in the calculation of each line. The thick line at the top of the figure shows the mean residential electricity consumption per residential user, based on administrative data about the characteristics of the distribution utilities.

Both the survey and administrative data show the same downward trend in household electricity consumption between 2009 and 2020. Average consumption fell by more than half, from over 100 kWh per household-month to about 40 kWh per household-month. The survey data allows us to decompose the sources of this change. It comes from a combination of (i) a decline in consumption within each household, possibly due to more efficient energy-using durables such as lightbulbs and the substitution of grid electricity by solar, and (ii) the newly connected households having lower consumption than the households that had a connection before 2010. While the trend is the same, the household

undertake a census of all structures within a 600-meter radius of 150 electricity transformers in rural Kenya. Despite the availability of the distribution network in their communities, only 5 percent of households and 22 percent of businesses have an electricity connection.

Figure 4: Real energy prices for surveyed households, by parish, 2009–2019



consumption from the survey data is lower than the average residential consumption from the administrative data. This likely reflects high electricity consumption by a small number of high-income households that are underrepresented in the household survey.

2.3 Energy prices

Umeme is the major electricity distributor in Uganda, with more than 90 percent of the total number of electricity customers. There are nine small distribution companies (or co-operatives in rural areas) covering 13 service territories. Some are operated by private operators and others by the Uganda Electricity Distribution Company Ltd. (UEDCL). Quarterly data on residential electricity prices for each distribution company is from the Electricity Regulatory Authority.

Umeme has a two-tier, increasing block tariff for electricity. The consumption quantity for the first tier is 15 kWh per month. Of the households for which we observe monthly consumption, 86 percent have consumption higher than 15 kWh. Given the low proportion of households on the first tier, we do not explicitly model the nonlinear price structure.

Instead, we assume that all Umeme households face the second tier price.

We use connection charge data for 2017 and 2018 from MFPED (2018). We supplement this information with hand-collected historical connection charges from the websites of the distribution companies, archived by the Wayback Machine. At the start of 2018, Umeme charged 139,300 Ugandan shillings (US$38) for a connection that does not require a pole, and 367,300 Ugandan shillings (US$100) for connection with a pole. Connection charges for other firms were much higher than those for Umeme. We make the assumption that the connection charge for households in urban areas is the "no pole" price and for households in rural areas the "one pole" price.

In November 2018, the Ugandan government implemented the Electricity Connections Policy that reduced the price of an electricity connection (both with and without a pole) to only the inspection fee of about US$10. This subsidy policy reimbursed electricity distributors for the cost of each connection. However, high demand for connections and delays in reimbursing the distributors meant that households who were prepared to pay the full connection charge received priority over the subsidized households. In late 2020 (after the end of our sample period), the subsidy policy was temporarily suspended.

Monthly price data for other energy commodities in Uganda are published by the Uganda Bureau of Statistics in their Consumer Price Index reports. These include price data in seven cities for propane, gasoline, diesel, firewood, charcoal, and kerosene. There is some geographical dispersion in energy prices although the correlation of price changes is high.

Figure 4 shows the mean parish-level real prices for the observations in our dataset. The regulated electricity prices rose gradually in real terms, while kerosene prices declined. Because the connection charges remained constant in nominal terms for most of our sample period, they declined in real terms. The large drop in 2019 reflects the impact of the Electricity Connections Policy. The bottom right panel shows that solar panel prices declined substantially in real terms during our sample period. The panel prices are the average reported asset value for the panel for solar households.

2.4 Distribution utility financial data

The electric utilities in Uganda buy the electricity they sell from the grid operator, UETCL. The Electricity Regulatory Authority sets the price that each firm pays for its wholesale electricity purchases. For Umeme, there are three wholesale prices based on the time of day: peak, shoulder, and off-peak. We calculate the weighted average price using the

Table 1: Summary statistics for households in fuel choice and electricity consumption samples

Variable	Full sample					Elect. sample	
	Min.	Mean	Med.	S.D.	Max.	Mean	Med.
Grid connection (0/1)	0.00	0.17	0.00	0.38	1.00	1.00	1.00
Distance to grid (km)	0.00	2.14	0.00	8.02	91.46	0.03	0.00
Electricity price ($/kWh)	0.13	0.18	0.18	0.02	0.21	0.19	0.19
Kerosene price ($/L)	0.07	0.09	0.09	0.01	0.11	0.08	0.08
Solar potential (MWh/kWp)	1.13	1.59	1.57	0.10	1.80	1.56	1.55
Expenditure ($/mth)	5	182	122	261	13,631	419	307
Expenditure p.p. ($/mth)	2	43	27	76	4,544	98	71
Number of adults	0.00	3.65	3.00	1.98	19.00	3.68	3.00
Number of children	0.00	1.48	1.00	1.42	11.00	1.28	1.00
Dwelling is house (0/1)	0.00	0.67	1.00	0.47	1.00	0.66	1.00
Number of rooms	1.00	2.34	2.00	1.43	20.00	2.47	2.00
Owner-occupied (0/1)	0.00	0.78	1.00	0.41	1.00	0.58	1.00
Urban (0/1)	0.00	0.26	0.00	0.44	1.00	0.77	1.00
Consumption (kWh/mth)						44.33	32.00
Reliability (0-1)						0.79	0.83
No. of observations			21,179			2,094	

Notes: The first five columns show summary statistics for the full sample used to estimate the fuel choice model. The last two columns show summary statistics for the subsample of connected households with electricity consumption information, used to estimate the consumption model. The mean, median, and standard deviation are calculated using the survey sampling weights. Monetary values are in real (2018) U.S. dollars.

purchased in each period. At the start of 2018, the weighted average wholesale for Umeme was 291 Ugandan shillings per kWh (8 US cents per kWh) (ERA, 2022).

For each kWh that a household consumes, Umeme has to buy more than one kWh from the transmission grid, to cover technical losses in the distribution network. The proportion of electricity lost due to these technical losses is assumed to be 15 percent.

The financial cost to the utility of labor and materials for connecting a new customer will differ based on the number of connections in a neighborhood that can be provided at the same time and whether or not an additional electricity pole is required. For our base analysis we assume the cost of a connection is US$200 (in real 2018 dollars). This is approximately the average cost of connections with and without a pole. For discounting future earnings from a connected household, we assume a real annual discount rate of 5 percent.

A final requirement to calculate the profitability of connecting an additional customer is the variable component of administrative and network maintenance costs. By how much do these increase as the result of one extra connection? We used quarterly data on the number of customers, the quantity of electricity sold in kWh, and the administrative and network maintenance costs for each electricity utility in Uganda. We then estimated Equation (1) with utility and quarter-of-sample fixed effects α_i and δ_t.

$$\log(expenses_{it}) = \beta_1 \log(customers_{it}) + \beta_2 \log(kWh_{it}) + \alpha_i + \delta_t + \varepsilon_{it} \tag{1}$$

Using the estimated coefficients we predicted the additional operating expenses for Umeme from adding one more customer with the average domestic consumption in the first quarter of 2018. This predicted cost is US$1.88 per customer per month.

3 Empirical methodology

We estimate a discrete-continuous model for fuel choice and electricity consumption of Ugandan households, adapted from the model used by Mansur et al. (2008). Households are assumed to maximize their utility by jointly choosing both the type and quantity of fuel that they use. We then use this model to predict the probability of having an electricity connection, as well as the electricity consumption conditional on being connected, for use in the optimization model of the electric utility.

3.1 Household fuel choice model

The first stage of our model is a multinomial logit model of the choice of fuel used for lighting. The available lighting sources for the household are a grid electricity connection, kerosene lanterns, small solar kits, and the outside option of either no lighting or a primitive fuel such as firewood. Households select the fuel that maximizes their utility. The fuel choice depends on the capital cost of the fuel (either the grid connection fee or the price of a kerosene lamp or solar panel), the variable price of the fuel, the availability of the fuel at the household's location (hours of grid electricity or annual solar potential), household income, as well as household and dwelling characteristics.

We partition these four categories into two nests: unimproved sources (kerosene and the outside option) in B_1, and improved sources (electricity and solar) in B_2.

Let V_{ij} be the indirect utility of household i from fuel choice j in nest B_k:

$$V_{ij} = \tilde{V}_{ij} + \varepsilon_{ij} \tag{2}$$

where ε_{ij} is distributed as a generalized extreme value distribution with the following cumulative distribution (Train, 2009):

$$\exp\left(-\sum_{k=1}^{2}\left(\sum_{j\in B_k} e^{-\varepsilon_{ij}/\lambda_k}\right)^{\lambda_k}\right)$$

and $\tilde{V}_{ij}$ is given by:

$$\tilde{V}_{ij} = \beta_1 K_j + \beta_2 K_j^2 + \boldsymbol{z'_{it}}\boldsymbol{\delta_j}$$

The expression for $\tilde{V}_{ij}$ also includes a quadratic in the initial capital cost of the energy source j, K_j. For an electricity connection, this capital cost is the upfront connection charge set by the distribution utility.

Characteristics of the household and the lighting sources $\boldsymbol{z_{it}}$ may differentially affect the indirect utility from lighting fuel choice j, captured by the fuel-specific parameter vector δ_j. Household characteristics included in the model are the log of household expenditure, the number of adults and children, the size of the dwelling, and whether it is located in an urban area. Fuel characteristics in the model are the (logged) prices of electricity and kerosene, the annual solar potential in the household's parish, the density of electricity lines in the parish, and (for parishes that are unconnected to the distribution network) the distance to the nearest distribution line.

Households are assumed to choose the fuel source alternative that maximizes their utility. With this assumption, and given the assumptions on the model structure and error term above, the probability that household i chooses fuel type j is:

$$\Pr_i(j) = \frac{e^{\tilde{V}_{ij}/\lambda_k}\left(\sum_{l \in B_k} e^{\tilde{V}_{il}/\lambda_k}\right)^{\lambda_k - 1}}{\sum_{m=1}^{2}\left(\sum_{l \in B_m} e^{\tilde{V}_{il}/\lambda_m}\right)^{\lambda_m}} \tag{3}$$

3.2 Household electricity consumption model

The second stage of our household model is the demand for electricity given that the household chooses to have an electricity connection. Electricity demand depends on the electricity price, household income, electricity reliability, and other household and dwelling characteristics.

The household consumption of electricity is given by the estimation equation (4):

$$\log(q_{it}) = \beta \log(p_{it}) + \gamma \log(y_{it}) + \boldsymbol{z'_{it}}\delta + \sum_{k \in K^-} \hat{\theta}_{ikt} + \alpha_i + \delta_t + \varepsilon_{it} \tag{4}$$

The dependent variable q_{it} is household i's electricity consumption during month t, measured in kWh. Other household characteristics are captured by the vector $\boldsymbol{z_{it}}$. These include the number of adults and the number of children in the household, the size of the dwelling, the type and ownership status of the dwelling, the nature of any improvements to the dwelling, and an urban/rural indicator.

The variable p_{it} is the electricity price (in Ugandan shillings per kWh) in the region of household i during month t. One challenge is that the regulated tariff for Umeme is a two-part, increasing block tariff. Households pay a low subsidized price for the first 15 kWh of consumption each month, then a higher price for each additional unit of consumption. The quantity on the first price tier is much smaller than the consumption of most households in the sample. For simplicity, we do not explicitly model the nonlinearity in the tariff. Instead, we assume that p_{it} is the regulated price per kWh on the highest consumption tier.

The variable y_{it} is the annual expenditure of household i, as measured at the survey date t.[10] The choice to use expenditure from the household survey, rather than income, reflects the considerable difficulty of measuring self-reported income on a household

10. In both the consumption and discrete choice model, we deduct the annualized capital cost of the fuel choice from household expenditure y_{it}, using an annual discount rate of 15 percent.

survey. This challenge is especially relevant for a rural setting in a developing country where few people have a stable salary. We make an implicit assumption that income and expenditure are fixed and do not depend on the choice of fuel source. If access to modern energy services increases household productivity, it is possible that expenditure might change based on the fuel choice. We assume that energy services provide consumption utility and do not enter as inputs into household production, so there is no feedback from fuel choice to household income or expenditure.

One potential concern is unobserved heterogeneity across households in preferences for energy consumption (Miller and Alberini, 2016). Our main specification uses a pooled estimator, treating repeated data for energy usage within the same household as independent observations. However, we also estimate a model with household fixed effects, α_i, which absorb all unobserved, time-invariant household characteristics.

Another potential issue with the use of panel data in this context is the possible secular trend in energy consumption. This trend might occur within households: for example, households with an electricity connection may acquire new appliances and so increase their consumption of household energy services. Alternatively, the household might replace existing appliances (or lightbulbs) with more efficient models, reducing electricity consumption over time. We allow for these trends by including time (survey wave) fixed effects δ_t in the model estimation.

The econometric challenge is that we only observe the electricity quantity for those households that chose to obtain an electricity connection. This creates a sample selection bias in the electricity demand estimates, due to possible correlation in the error terms in the two equations. For example, suppose a household has an unobserved taste for food refrigeration. This would show up as both a positive shock in the demand for an electricity connection and a positive shock in the conditional demand for electricity. We correct for this potential selection bias by including multiple selection correction terms θ_k in the fuel demand equations, one for each of the alternative lighting fuel choices (Dubin and McFadden, 1984; Mansur et al., 2008).

3.3 Distribution utility model

We use our estimated model of household fuel choices to develop a model of an electricity distribution utility. The utility is assumed to be a profit-maximizing monopolist within its service territory. The government regulator sets the tariffs, including fixed and per unit charges. The only choice variable for the distribution utility is the initial connection charge

K.

The profit equation for the distribution utility embeds the household fuel choice and the electricity consumption models. The distributor will choose the connection cost K to maximize the net present value of profits from providing a connection:

$$\max_K \pi = \sum_i \Pr(connect_i|K) \left(\frac{1}{\delta}((p_k - c_k)q_i + F_k - C_F) + K - C\right) \tag{5}$$

Here C is the cost for the utility of providing a connection, δ is the distributor's discount rate, p_k is the regulated electricity price received by the distributor, c_k is the per unit cost of procuring electricity, q_i is the annual demand for electricity for household i conditional on having a connection, F_k is the annual fixed charge for one household connection, and C_F is the annual fixed cost associated with an additional connection. The sum is over all households i in the distributor's service territory.

The first component of the profit expression in parentheses in Equation (5) is the distributor's profit or loss from the sale of electricity. The total quantity of electricity sold will depend on the connection charge K. A lower connection charge will increase the number of connected households, with Equation (3) providing the relationship between the connection charge and the connection probability. Those households that are connected at the margin typically will have lower consumption. The electricity quantity q_i consumed by household i, conditional on having a connection, is given by equation (4).

The second component of the profit expression is the distributor's profit or loss on the fixed and capital costs and charges—everything that does not depend on the quantity of electricity sold. All of the costs and charges are "per household". We multiply these costs by the probability of choosing to have a connection, which again depends on the connection charge K through equation (3).

The model assumes that all customers pay their electricity bill. Customer nonpayment is a troubling issue for utilities in many Sub-Saharan African countries, although the rollout of prepaid metering has ameliorated this problem, including in Uganda (Jack and Smith, 2020).

The focus of our model is on the "last meter" connection of households to an existing distribution network. We assume that the capital cost of a connection is the same for all households. In practice, it may be cheaper to connect several neighboring households at the same time, especially if one pole can serve multiple dwellings. The current model ignores this potential interaction between the decisions of different households.

Table 2: Marginal effects for fuel choice probabilities with respect to selected regressors

Variable	Other	Kerosene	Electricity	Solar
Elasticities with respect to:				
Household expenditure	-0.57	-0.51	1.75	0.71
Electricity price	1.84	-1.40	-1.44	3.64
Kerosene price	-1.76	0.95	-0.05	-0.72
Semi-elasticity effect of one-unit increase:				
Local grid density (km/km2)	0.06	0.04	0.38	-0.63
Distance to grid (km)	0.09	0.02	-0.23	0.06
Number of adults	0.02	0.05	-0.16	-0.03
Number of children	0.01	0.08	-0.24	-0.02
Dwelling rooms	-0.11	0.03	-0.05	0.11
Urban (0/1)	-0.22	-0.38	1.89	-0.34

Notes: The first section reports the elasticity of the fuel choice probability with respect to each of the variables. The second section reports the semi-elasticity of the fuel choice probability with respect to a one-unit change in each of the variables.

This model is sufficiently general to capture the interactions between the regulator, distribution firms, and consumers. For example, if the regulator sets a nonlinear electricity tariff, so that consumers with low consumption pay less than the cost c_k, then the distributor would want to set K high enough to screen these customers out of the market.

4 Results

4.1 Fuel choice model

A core part of our analysis is the discrete choice model of the household's decision about their primary energy source for lighting. There are four choices considered: no or primitive fuels, kerosene, electricity, or solar. Any household with an electricity connection is assumed to use this as their primary energy source. Otherwise, the household's choice depends on the self-reported use of each fuel for lighting.

There is no clear interpretation of the coefficients from the mixed logit estimation, and so these are not reported. Instead, we show elasticities and semi-elasticities of the fuel choice probabilities with respect to the explanatory variables of interest (Table 2). A higher electricity price reduces the probability of choosing to have an electricity connection and increases the probability of using solar. The elasticity of the connection probability with respect to the electricity price is -1.44. Higher incomes increase the probability of choosing to have either a connection or solar, with an income elasticity of the connection probability of 1.75.[11]

The second part of Table 2 shows semi-elasticities for the adoption probabilities with respect to a unit change in each of the variables. The estimated signs of these effects are as expected. A denser electricity grid, or a reduction in the distance to the network, both increase the probability of choosing to have an electricity connection. Large families are less likely to have electricity. Finally, after controlling for the other determinants, households in urban areas are 189% more likely to have a connection than households in rural areas. Urban households are less likely to use solar, kerosene, or other fuel sources for lighting.

4.2 Fuel demand model

Estimation results for Equation (4) are shown in Table 3. Each observation is a household's electricity consumption in one month, for those households with an electricity connection. Column 1 only includes parish fixed effects and no time effects. The electricity price has a negative and statistically significant effect on consumption, with an implied price elasticity of -0.48. Income has a positive effect on consumption, with an implied income elasticity of 0.20. Households in urban areas and those with larger dwellings have higher electricity consumption.

Column 2 adds time fixed effects for the seven survey waves. Controlling for time effects reduces the magnitude of the estimated price elasticity to -0.25 (no longer statistically significant). There is little change to the magnitude or precision of the other estimates. Owner-occupied houses have higher electricity consumption that rented houses or other types of dwellings. Dwelling size continues to have a positive effect on electricity consumption.

Finally, column 3 in the table adds household fixed effects. In this version of the model, all of the coefficients are estimated using within-household variation in electricity consumption over time. There are up to seven observations of monthly electricity consumption for a particular household over a 10-year period. In this model with both household and time fixed effects, the magnitude of the price effect is larger but remains statistically

11. The elasticity results for the kerosene price are somewhat anomalous: higher kerosene prices increase the probability of using kerosene and reduce the probability of the other fuel choices. These results are likely a consequence of an unobserved determinant of households' decisions to switch away from kerosene. Kerosene prices alone cannot explain the trend, as both real kerosene prices and kerosene use declined during our sample period.

Table 3: Estimation results for household fuel demand equations (log-log model)

	Log electricity consumption		
	(1)	(2)	(3)
Log price	-0.476**	-0.253	-0.432
	(0.211)	(0.338)	(0.455)
Log expenditure	0.198***	0.215***	0.111*
	(0.032)	(0.030)	(0.066)
Number of adults	0.005	0.004	0.0004
	(0.009)	(0.009)	(0.019)
Number of children	0.013	0.010	0.053*
	(0.015)	(0.016)	(0.028)
Urban area (0/1)	0.140***	0.164***	0.106
	(0.051)	(0.053)	(0.083)
Number of rooms	0.050***	0.033**	0.010
	(0.014)	(0.014)	(0.026)
Owner-occupied (0/1)	0.077	0.086	0.032
	(0.055)	(0.054)	(0.117)
House (0/1)	0.062	0.089*	0.034
	(0.052)	(0.051)	(0.084)
Reliability (0-1)	-0.050	-0.025	0.024
	(0.088)	(0.090)	(0.127)
θ_{other}	0.066	0.089	0.109
	(0.076)	(0.078)	(0.113)
$\theta_{kerosene}$	-0.121**	-0.102*	-0.067
	(0.059)	(0.058)	(0.096)
θ_{solar}	0.047	0.003	-0.053
	(0.058)	(0.058)	(0.087)
Fixed effects			
Parish	Y	Y	Y
Survey wave	N	Y	Y
Household	N	N	Y
Observations	1,955	1,955	1,955
R^2	0.395	0.406	0.658

Notes: Standard errors in parentheses are clustered by parish to account for correlation in the errors for neighboring households in the same parish as well as correlation within a household over time.

insignificant. The magnitude of the income effect estimated using the within-household variation is about half as large, but remains statistically significant at a 10% level. Other household characteristics are estimated much less precisely, reflecting the limited variation in these variables within a household over time. One interesting exception is the number of children in a household: each additional child increases electricity consumption by about 5 percent. There is no effect of additional adults in the household.

All three versions of the model include the θ terms for the predicted probability of choosing the alternatives to an electricity connection. These terms correct for the sample selection bias caused by only observing electricity consumption for those households that choose to have a connection. The only statistically significant term is on $\theta_{kerosene}$: households with a higher predicted probability of choosing kerosene for lighting will use less electricity, conditional on having a connection.

4.3 Distribution utility model

We use the estimated models of fuel choice and electricity demand to analyze the profitability of an electricity distribution utility, focusing on how profits depend on the electricity price and connection charge. We calculate revenues as the electricity price multiplied by the total quantity of electricity demanded, where the latter is the sum across all households of the quantity of electricity consumed conditional on having a connection, multiplied by the probability of having a connection. There are three types of cost that we consider: the wholesale cost of electricity (scaled up to reflect distribution losses), the ongoing variable costs of providing a connection, and the upfront capital costs of a connection. We do not consider fixed costs that are independent of the number of connections.

This stylized model captures the economic relationships between the household and the distribution utility behavior. Higher connection charges increase the profitability of a connected household for the utility but reduce the probability of a household connecting. Lower electricity prices increase the quantity of electricity demanded, but if they are too low, then the distribution utility will lose money on the connected households. The utility offsets this loss by setting higher connection charges, which increases profits by both reducing the number of connected households and increasing revenues for the households who do connect.

We first analyze the case of a distribution utility with a low price for supplying electricity (first panel of Table 4). At the price of 15 cents/kWh and a zero connection charge, the average consumption of electricity for connected households is 59 kWh per month. Each column in the table shows the effect of a different connection charge. If the connection charge is \$0, then 29.3 percent of households will choose to connect. The proportion of households with an electricity connection decreases for higher connection charges, dropping to 5.8 percent of households for a connection charge of \$300.

The utility earns lower profits for each connected household if it sets a low connection charge. With a connection charge of \$0, the distribution utility earns \$1.10 per month for each connected household. Raising the connection charge has two effects. The average consumption of the connected households increases, because the higher connection charge selects for those households with higher electricity consumption who value the connection more. Second, there is additional revenue provided by the higher connection charge. Overall, gross profit for the connected households increases to \$5.49 per month with a connection charge of \$300.

The relevant variable for the firm's choice of connection charge is not the gross profit on the connected households, but instead the overall gross profit for both connected and unconnectred households in the service territory. For the total population of connected and unconnected households, the average gross profit is \$0.32 per month with a connection charge of \$0 and \$0.32 per month with a connection charge of \$300. For the values of the connection charge shown in the table, the utility maximizes its profit per actual and potential customer with a connection charge between \$100 and \$150.

The result is different for a distribution utility that charges a higher regulated price for electricity (second panel of Table 4). With a price of 25 cents/kWh, there are fewer connected households and the average consumption for connected households at a connection charge of zero is slightly lower: about 61 kWh per month. The small change in electricity consumption between the two panels reflects the relatively inelastic price elasticity of demand for electricity from the estimation results in Column 2 of Table 3.

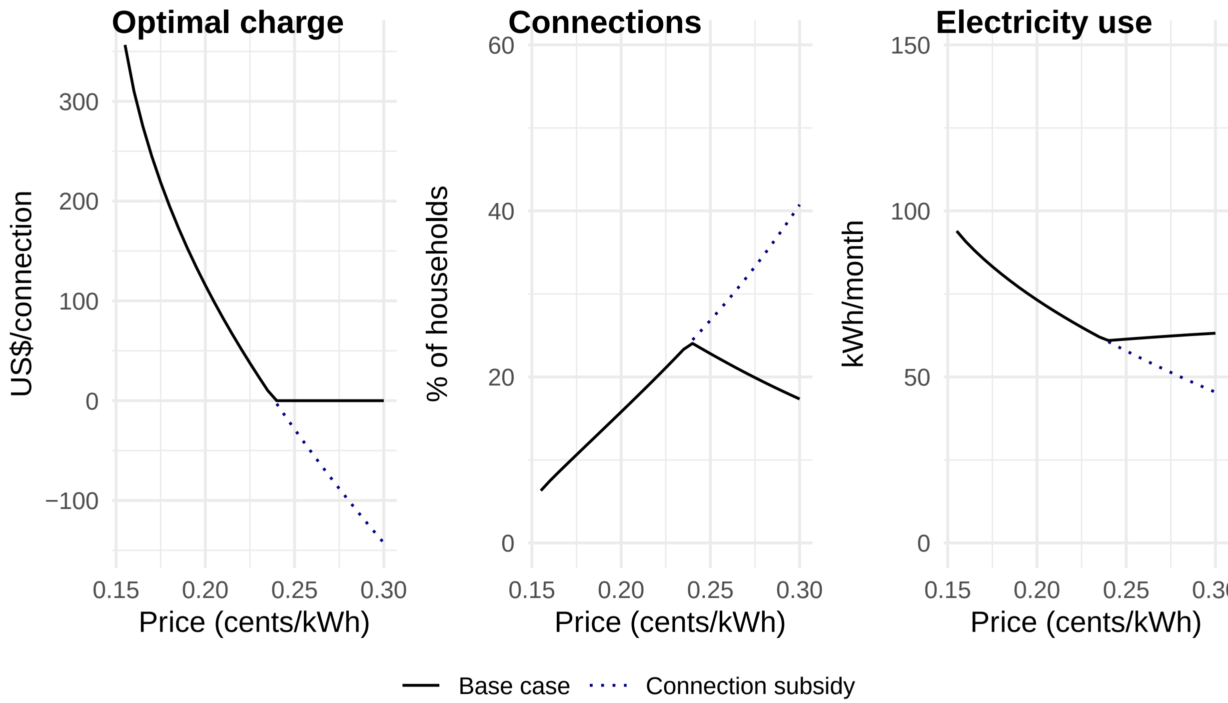
The higher electricity price in the second panel is sufficient to cover all costs associated with supplying electricity. Gross profit for connected households is positive, varying from \$3.87 per month for a connection charge of \$0 to \$9.01 per month for a connection charge of \$300. In each column, the proportion of connected households is slightly lower when the electricity price is higher, reflecting the effect of a higher price on the value of a connection. For example, with zero connection charge, the proportion of connected households is 29.3% with a price of 15 cents per kWh and 22.8% with a price of 25 cents per kWh.

With a higher regulated electricity price, the optimal connection charge is lower. For the connection charges shown in the table, the maximum profit per potential customer is

Table 4: Effect of connection charges on distribution utility profitability

	Connection charge (US$)						
	0	50	100	150	200	250	300
Price = US$0.15 per kWh							
Connected %	29.34	22.55	17.21	13.06	9.89	7.52	5.78
All households							
Av. consumption (kWh/month)	17.45	14.85	12.32	9.99	7.96	6.30	5.00
Gross profit (US$/month)	0.32	0.41	0.44	0.44	0.40	0.36	0.32
Connected households							
Av. consumption (kWh/month)	59.47	65.84	71.56	76.46	80.50	83.80	86.47
Gross profit (US$/month)	1.10	1.80	2.56	3.33	4.08	4.80	5.49
Price = US$0.25 per kWh							
Connected %	22.80	17.01	12.55	9.19	6.73	4.96	3.71
All households							
Av. consumption (kWh/month)	13.99	11.39	9.00	6.94	5.29	4.02	3.08
Gross profit (US$/month)	0.88	0.82	0.73	0.61	0.51	0.41	0.33
Connected households							
Av. consumption (kWh/month)	61.37	66.99	71.70	75.50	78.53	80.95	82.91
Gross profit (US$/month)	3.87	4.84	5.79	6.68	7.51	8.29	9.01

Figure 5: Electricity connections, household income, and distance to distribution network

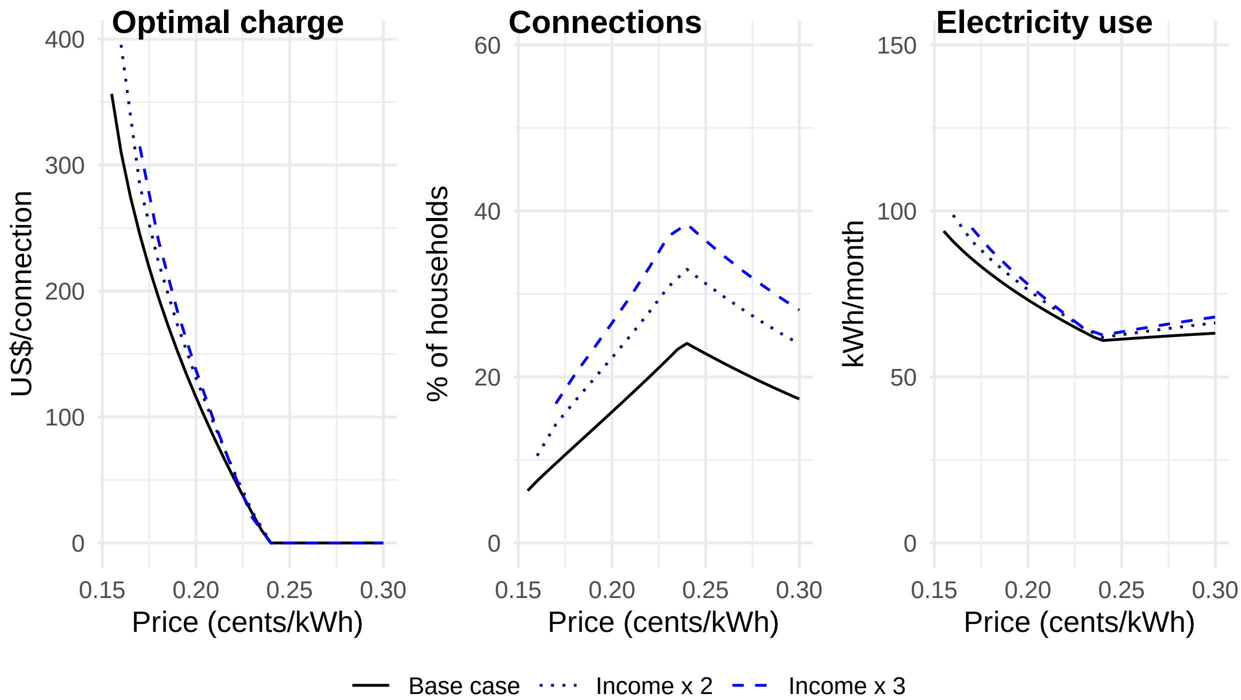


attained with a connection charge of zero, giving an average gross profit of about $0.88 per household in the service territory.

Optimal connection charges are lower for higher regulated electricity prices (Figure 5). For an electricity price of 27 cents/kWh, the optimal connection charge would be zero (left panel), and this connection charge would maximize the number of connected households (center panel). For electricity prices below 27 cents/kWh, the connection charge that would maximize utility profits increases, leading to a drop in the number of connected households. This decline is because the higher upfront connection cost outweighs the value of a lower electricity price for households in their connection decision. For electricity prices above 27 cents/kWh, the number of connected households declines slightly, given that the connection charge remains zero and the value of a connection is lower at higher electricity prices.

Our model of the distribution utility suggests the theoretical possibility of setting a negative connection charge for high regulated tariffs. For electricity prices above 27 cents per kWh, the utility would maximize profits by paying households to connect to the electricity grid (dotted lines in Figure 5). However, even though households are paid to connect, the high price they pay for their consumption still limits the value of the

Figure 6: Sensitivity of results to household expenditure

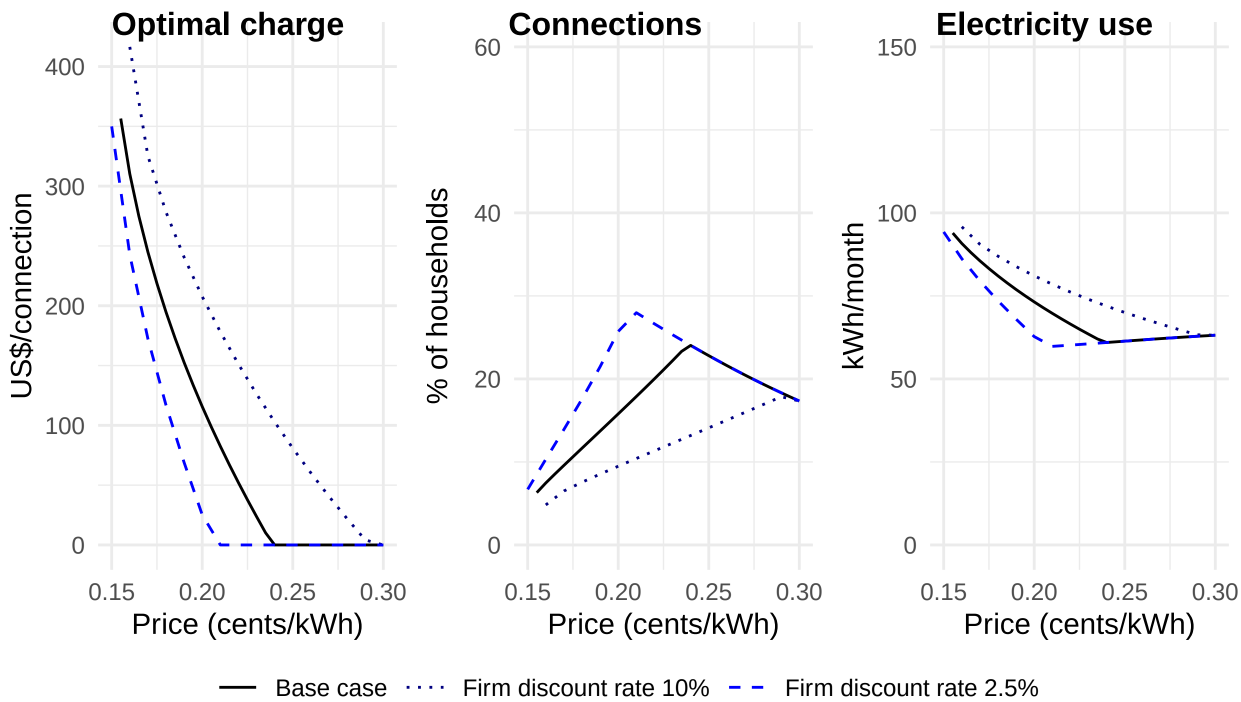


connection. At an electricity price of 30 cents per kWh, the utility would pay households more than $100 to be connected, and about 40 percent of households would choose to have an electricity connection (center panel of Figure 5).

Higher household incomes would increase the demand for electricity, conditional on having a connection (left panel of Figure 6). The effect on the connection probability is somewhat mitigated by the distribution utility optimally setting a higher connection charge. Nevertheless, higher incomes will still lead to much higher electricity connection rates: close to 40 percent for a tariff of 24 cents per kWh.

Changes in the parameter assumptions for the financial model of the utility firm will affect the optimal connection charge. Higher discount rates imply that the utility attaches less value to the future stream of profits from having a connected household. This increases the optimal connection charge (left panel of Figure 7) and reduces the number of connections (center panel). Given the higher connection charge, only customers with higher electricity demand will choose to connect, leading to higher consumption for the connected households (right panel).

Figure 7: Sensitivity of results to real discount rate assumption



5 Conclusion

High electricity connection charges are a primary barrier to electricity access and a major contributor to low electrification rates in Sub-Saharan Africa. It is a trivial observation that lowering the connection price will increase the number of connections demanded. A more fundamental question is the reason for the distribution utilities to set high connection charges in the first place. Without understanding the economic determinants of connection charges, any attempts to increase electrification by directly subsidizing these charges may be costly and ineffective.

The household and utility firm model demonstrates how low regulated tariffs might lead to high connection charges and low electrification rates. Why would utility regulators set low electricity tariffs given the potentially detrimental effects on the financial and economic performance of the sector? Note that low tariffs are most visible and most beneficial to those households who already have an electricity connection. These are likely to be high-income, urban, educated households—a natural political constituency for the regulator.

The households who suffer most from the low regulated tariffs are those who would choose to have an electricity connection if offered higher prices and lower connection charges than the status quo. The harm caused to these households is much less visible. If anything, households will blame the distribution utility for setting high connection charges, rather than blame the regulator for setting low tariffs. The regulator is much less likely to consider this group in its tariff-setting process.

These considerations highlight the importance of ensuring the regulatory agency is independent and free from political influence. Ideally, the regulator should maximize the welfare of all households, not just the ones with existing connections. Based on the analysis in this paper, this may involve setting higher, not lower, tariffs.

The analysis has several limitations. First, the household and utility firm models are static. The regulator sets the tariff, the utility firm sets the optimal connection charge, and the household then reoptimizes its choice of fuel source. For the case of electricity, this would imply that a household can costlessly move to a dwelling without a connection if having electricity is no longer optimal at the new prices. Real estate prices would adjust to reflect changes in connection charges.

In reality, we might expect that the household and utility firm decisions are dynamic. For example, it may be optimal for a utility firm to act as a durable good monopolist and start by setting a very high connection charge. Only households with very high willingness-to-pay for a connection will connect at this price. Over time, the utility firm could set the connection charge lower and lower, capturing a larger and larger share of households. However, as suggested by the Coase conjecture, forward-looking households might wait to connect in anticipation of lower future connection charges. This type of dynamic behavior is not allowed for in the model.

An additional assumption in the analysis is that the household makes a utility-maximizing decision in its choice of fuel source. Potential market failures make this unlikely. For example, the household might have imperfect information about the health effects of fuel sources such as kerosene that create indoor air pollution. Although consumption utility from the polluting fuel source includes the pollution damage, uninformed households would ignore this effect in making their choice. Imperfect information increases the probability of choosing a polluting fuel such as firewood or kerosene.

The analysis suggests that policies designed to address energy market failures in developing countries should target the source of the market failure. For example, imperfect information about indoor air pollution justifies the provision of better information, not subsidies for cleaner fuels. Targeted policies are especially relevant for countries with private investment in restructured electricity markets. Profit-maximizing firms may absorb much of the benefit of connection cost subsidies, and these subsidies may have little effect on electrification rates. Instead, by setting cost-recovery tariffs, the regulator can ensure that distribution utilities have an incentive to increase the number of connections.

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