Rwanda's Path to Universal Electricity Access: Consumption Trends, Tariff Impact, and Challenges Ahead

Joel Mugyenyi[1*], Bob Muhwezi[2], Simone Fobi[1], Civian Massa[2], Jay Taneja[2], Nathaniel J. Williams[3], and Vijay Modi[1]

[1]Department of Mechanical Engineering, Columbia University
[2]Department of Electrical & Computer Engineering, University of Massachusetts Amherst
[3]Golisano Institute for Sustainability, Rochester Institute of Technology
{jm5352,sf2786,modi}@columbia.edu, {bmuhwezi,ckmassa,jtaneja}@umass, njwgis@rit.edu

***Abstract*—Rwanda has made significant strides towards achieving universal electricity access recently. This paper examines consumption trends and patterns among households connected to the grid from 2013 to 2019, leveraging a unique dataset of prepaid electricity purchases provided by the national utility. Our analysis seeks to answer two pivotal questions: One, how have electricity consumption patterns evolved among customers over time? Two, how has household consumption responded to changes in the tariff structure? Employing an innovative approach, we transformed sporadic prepaid electricity purchases into an equivalent monthly consumption cadence to enhance the analytical process. The data shows that recently connected customers, more likely to be rural, exhibit lower consumption levels compared to older customers, more likely to be urban. This study illuminates the disparities in consumption patterns between rural and urban customers. Additionally, tariff reductions targeting the lowest consumption tier led to a decrease in total electricity expenditure, suggesting the presence of competing financial obligations within household budgets. Notably, the potential impact of efficiency improvements in lighting and smartphone usage remains unexplored and warrants further investigation. This research highlights to policy makers the intricate relationship between affordability, consumption habits, and utility strategies in the context of increasing electricity access.**

***Index Terms*—Rwanda; tariffs; consumption; growth; rural**

I. Introduction

Rwanda, a country with a GDP per capita of 999 USD as of 2024 (World Bank, 2020), has made significant strides in connecting its population to the grid, soaring from a mere 10% (World Bank, 2020) in 2011 to an impressive 50% (NISR Census, 2023) by 2023. Over the span of 12 years, Rwanda succeeded in connecting over 1 million customers, constituting 34% of all households in the country according to the most recent census (NISR Census, 2023) . Such an achievement is remarkable, particularly when compared to countries with similar income levels. Throughout the 2010s, Rwanda experienced a staggering 380% relative increase in electricity access, ranking among the highest globally, surpassed only by Guinea-Bissau and Liberia, which have significantly lower access rates at 33.3% and 27.5%, respectively (GCDL, 2020). This progress can be attributed to the government's unwavering commitment to universal electrification (IDA, 2018).

In the global south, few countries have attained such rapid electrification, especially at Rwanda's GDP levels. Nonetheless, such remarkable progress does not come without its challenges. As electricity is introduced to millions of households as a new energy source, it becomes crucial to understand how households adopt it and how its pricing through tariffs influences their usage. Many of these households are situated in rural and remote areas, owing to underdeveloped transportation infrastructure (USAID, 2024). Understanding their consumption patterns, particularly in light of evolving technologies such as more efficient lighting like LED bulbs and communication devices like smartphones, remains a significant challenge.

Kenya is another country that experienced rapid electrification progress. Between 2010 and 2015, approximately 1.7 million (KPLC, 2015) new connections were made in the country, representing about 20% of Kenya's households by 2015 (Statista). A recent study indicated that those connecting to the grid in Kenya during this period exhibited progressively lower consumption levels and reached consumption peaks sooner than their counterparts who received grid connections earlier (Fobi et al., 2018). Low consumption among newer and particularly rural customers in Sub-Saharan Africa is also observed in several studies (Bensch et al., 2011; Boubakar et al., 2022; Lenz et al., 2017; Okoboi and Mawejje, 2016; Peters and Sievert, 2016; Taneja, 2018)

Increased consumption would enhance the financial sustainability of electricity utilities, as low consumption leads to lower revenues per customer (Taneja, 2018). Aware of this reality, utilities often implement tariff reforms aimed at boosting consumption levels to stimulate demand. However, a review of electricity tariff reforms in Africa suggests that the implementation of increasing block tariffs and lifeline tariffs tends to be poorly targeted, subsidizing the consumption of wealthier households at the expense of poorer ones and potentially reducing demand in the residential sector (Klug

*Corresponding author.
E-mail address: jm5352@columbia.edu (Joel Mugyenyi)

et al., 2022).

This study conducted a collaborative analysis with Rwanda Energy Group (REG), the principal electricity utility in Rwanda, to investigate the consumption patterns of households progressively connected to the grid from 2013 to 2019. Encompassing a vast sample of over 800,000 customers out of an estimated 1.323 million, and scrutinizing 361 million transactions over this period, we introduce an innovative methodology to transform prepaid transactions into monthly consumption metrics. Leveraging a novel, proprietary nationwide dataset of electricity consumers, our analysis offers empirical insights into the evolving demand patterns of customers on the grid. It delves into disparities in consumption among newly electrified households, juxtaposes urban versus rural areas, and examines customer responses to fluctuations in tariff structures.

By addressing these questions, this study unveils the evolution of customer consumption in the context of rapid electrification and low-income levels.

II. Rwanda Energy Group Utility Data

Rwanda's electrification endeavors are spearheaded by the Rwanda Energy Group also known as REG, established in 2014 (REG, 2024). REG operates through two subsidiaries: the Energy Utility Corporation Limited (EUCL) and the Energy Development Corporation Limited (EDCL). While EDCL focuses on the development of new energy generation and transmission infrastructure, EUCL is responsible for utility services and retailing electricity to end-users. This organizational division between EUCL and EDCL is designed to optimize project execution and cost-effectiveness, with EDCL primarily concentrating on development initiatives while EUCL handles grid maintenance and operation (REG, 2020).

The transaction dataset acquired from the Rwanda Energy Group offers a comprehensive perspective on the electricity consumption patterns of grid-connected customers over a seven-year period. This dataset comprises 361,029,383 prepaid historical electricity transactions/purchases made by 811,541 customers between October 2012 and April 2020. Each transaction is timestamped and associated with the corresponding customer and meter IDs, as well as the date the customer was connected to the grid. It's essential to note that this dataset does not encompass the entire population of grid-connected customers in Rwanda as of 2020. According to reports from the Ministry of Infrastructure, as of June 2020, Rwanda had a total of 1,092,081 customers (MININFRA, 2024).

The Ministry of Infrastructure issues annual reports showcasing the new electricity connections made within each fiscal year. We have aligned our transaction data with the fiscal year format used by the ministry which typically begins in July and ends in June of the subsequent year. Figure 1 illustrates that the official count of new connections closely matches the number from our dataset from 2006 to 2015. However, after 2015, a discrepancy emerges between the number of new connections in our transaction dataset and the numbers from official reports.

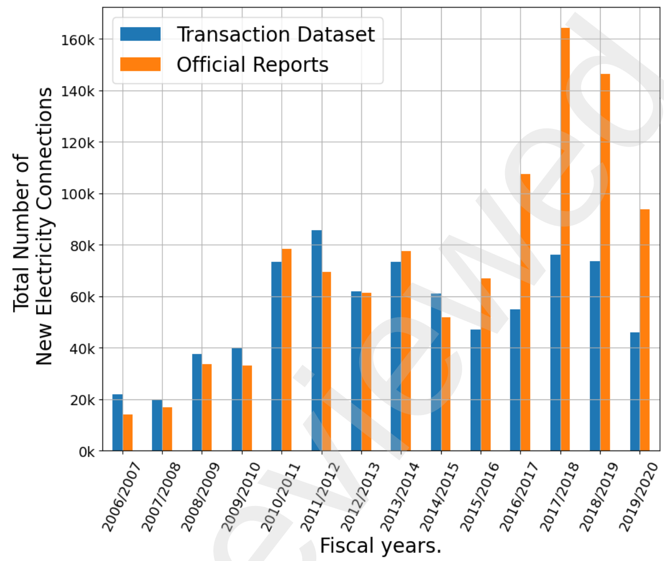


Fig. 1: Comparing Annual New Electricity Connections by REG: Analysis from Our Transactions Dataset vs. Official Reports

Figure 2 displays the grid access by district in Rwanda. To provide context regarding the spatial constraints of our transaction dataset, we utilize data from the 2022 Rwanda census (NISR Census, 2023), which outlines the number of households and electricity access rates in each district of the country[1]. We separately calculate access rates using our transactions data as indicated in Equation 1. We use the total customer count extracted from our transactions dataset alongside the total household numbers derived from the 2022 census. A comparison between census-reported access rates and those derived from our transaction dataset reveals close alignment in many districts, with notable discrepancies in others. For instance, the census reports an access rate of 88% in the capital city, Kigali, compared to 62% in our transaction dataset. It's worth noting that our transaction dataset concludes in mid-2020, whereas the census was conducted at the end of 2022. Hence, disparities are expected, as our dataset does not encompass new connections made in 2021 and 2022. Additionally, our transaction dataset contains data from only 15 of the 30 districts comprising Rwanda, as depicted in Figure 2, where districts lacking transaction data are shaded in gray. Comparing the total number of customers in our dataset with official reports, we note a discrepancy of 289,540 customers. We postulate that many of these missing customers reside in the grayed-out districts lacking transaction data.

$$\text{Access Rate} = \frac{\text{Customers in District}}{\text{Total Households in District}} \tag{1}$$

[1] We consolidate the three districts comprising the capital, Kigali, into a single district. This aggregation is to maintain consistency with our transactions dataset, where all districts forming the capital Kigali are merged into one. We maintain this format to facilitate a direct comparison with the 2022 census results.

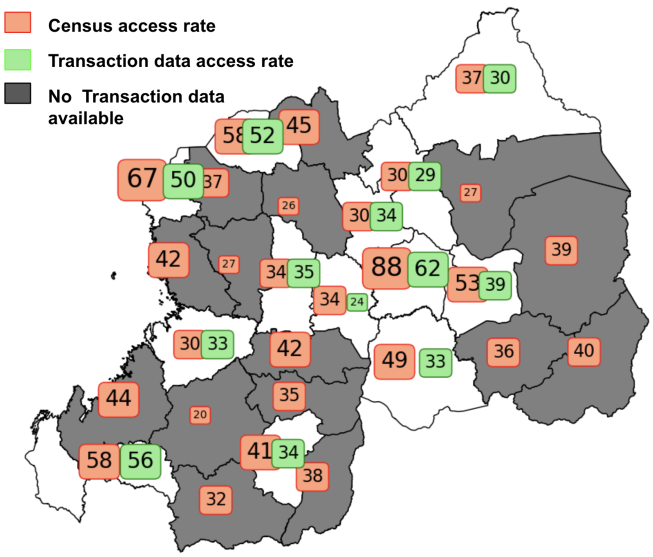


Fig. 2: Comparing Grid Access Rates in Rwanda: Analysis from Our Transaction Dataset versus 2022 Census Reports

Our transaction dataset also provides information on the quantity of electricity purchased and the corresponding tariff for the purchased units for each customer. Our analysis focuses solely on evaluating electricity consumption (measured in kWh) and the per kWh tariff, without considering associated taxes such as Value Added Tax (VAT).

Throughout the dataset period, there were occasional revisions in how customers were categorized as residential or non-residential. For this study, we adhere to the final categorization as of 2020. Based on this categorization, 88% of customers are classified as residential, with the remaining 12% categorized as non-residential. Non-residential entities include small commercial establishments, telecommunication installations, hotels, and health facilities. Large industrial customers are not included in the dataset.

This section highlights the temporal and spatial limitations of our dataset while acknowledging its coverage of the consumption patterns of the majority of customers connected to the national grid by 2020. In the following section, we delve into how we leverage this extensive dataset to gain fresh insights into the consumption patterns of Rwandan customers.

III. Methodology

A. From pre-paid purchases to monthly consumption

Prepaid meters have emerged as the predominant method for managing electricity consumption across sub-Saharan Africa (Jack and Smith, 2020). Facilitated by prepaid meters, prepaid transactions entail a payment method where customers purchase credit or units of service in advance, which are then gradually depleted as they utilize the service. This system is particularly favored in regions with unreliable or irregular service provision, as it mitigates the risk of non-payment and enables utilities to manage demand more effectively. However, one drawback of the prepayment system is its divergence from the postpaid system, where customers typically make payments at regular intervals, often at the end of each month. Prepaid customers exhibit less regular purchase patterns, as depicted in Figure 3, showcasing the dispersed nature of the total number of purchases customers make on an annual basis. For example in 2016, customers made a varying number of prepaid purchases, ranging from a single purchase to as many as 130 purchases. To provide context, making 130 purchases would equate to purchasing electricity approximately every three days.

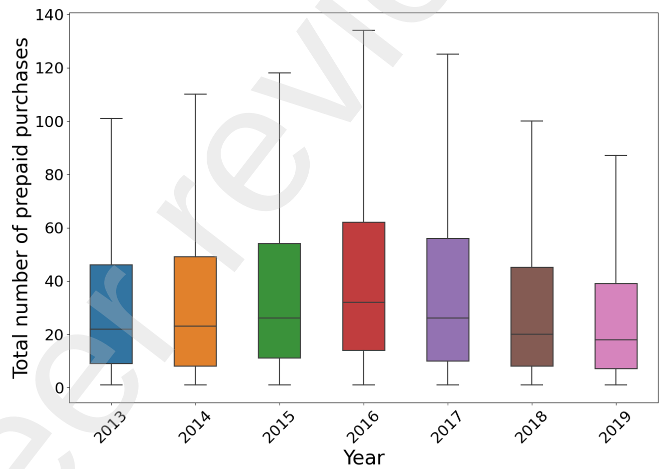


Fig. 3: Distribution showing the total number of prepaid electricity purchases customers made as computed from transactions dataset.

To ensure a consistent comparison of consumption patterns over time, we employ a pre-processing strategy similar to (Jack and Smith, 2020). This involves distributing customer consumption using transaction dates to construct average daily kWh consumption, assuming a constant rate of consumption per day between transactions. Unlike (Jack and Smith, 2020), we utilize the median purchase frequency for each customer in scenarios where customers have excessively long periods without purchases.

Our process unfolds as follows: for any two sequentially occurring purchase periods, if the time delta between the two periods was less than the median purchase frequency, the consumption was spread evenly between both periods on a daily basis. If the time delta between the two periods exceeded the median purchase frequency, the purchased units were spread over the median purchase frequency of the customer to prevent instances of very low consumption. Subsequently, the daily consumption is aggregated to monthly consumption. This process assumes that customers do not accumulate electricity credit on their meter. The transformation process effectively converts stochastic electricity purchases to monthly electricity consumption, facilitating further analysis. Importantly, the transformation preserves the customer consumption trends, as evidenced by Figure 4.

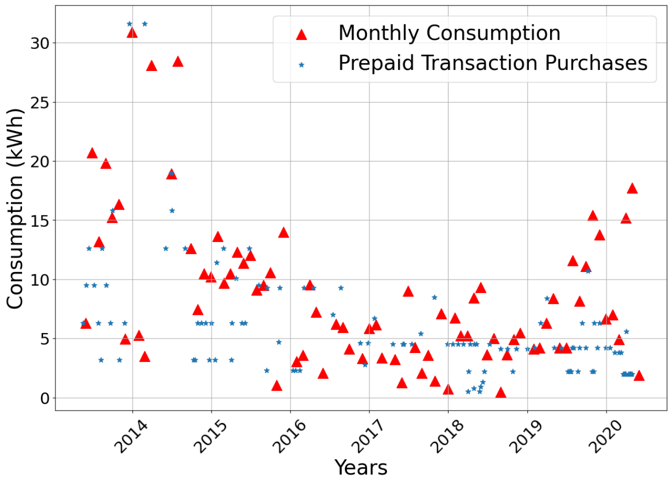


Fig. 4: Illustrative consumption history for a single customer selected at random. The blue dots show the customer's prepaid purchases, note that these are not at regular intervals and sometimes several purchases could be made within a month. The red triangles show the same customer's consumption aggregated for each month

B. Tariff Analysis for Residential Customers

Rwanda has undergone a series of tariff adjustments over the past decade. Figure 5 illustrates the electricity tariff structures for residential customers in Rwanda from 2006 to 2018. Prior to 2012, electricity tariffs were deemed below the cost of service, prompting the Rwanda Utilities Regulatory Authority (RURA), the agency tasked with regulating the energy sector, to approve a 20% increase in residential tariffs from 112 rfw to 134 rfw (RURA, 2018). Subsequently, residential tariffs saw a further 35% increase to 182 rfw in 2015, with authorities attributing this rise to increased generation costs stemming from continued reliance on thermal energy (The NewTimes, 2015a). Two years later, in 2017, a block tariff structure was introduced, entailing increased tariffs for high consumers while implementing "lifeline" tariffs for the lowest consumers. Given that most new connections are low consumers, the block structure aimed to enhance their affordability of electricity (IDA, 2018; The NewTimes, 2015b).

In our examination of tariffs and revenue, we concentrate on three consumption classes: low, medium, and high. These classes align with RURA's tariff block criteria established in 2018 (IDA, 2018). Equation (2) outlines the class definitions based on the average monthly electricity consumption $\bar{y}_i$ by customer i over a 12-month period preceding the tariff change. Table I offers an overview of the distribution of customers into the three consumption classes for the tariff periods in 2015 and 2017[2]. We have restricted our analysis to customers where the majority of monthly consumption falls within the same class, enabling us to focus on customers with stable consumption

[2]For the purposes of this study, a tariff period is considered the one year period preceding and proceeding a tariff change.

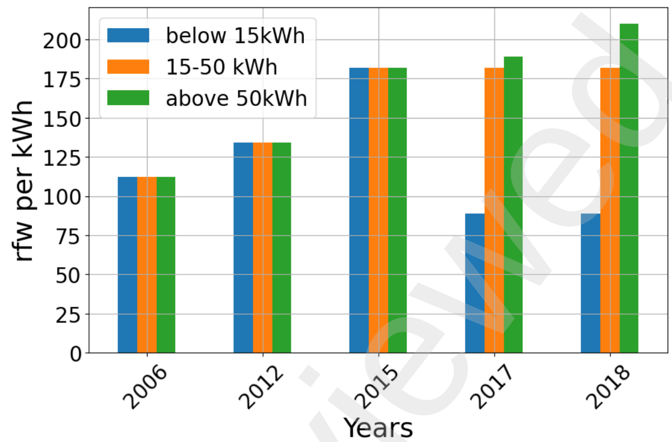


Fig. 5: Rwanda residential tariff structure from 2006-2018

TABLE I: Customer count by class considering only customers with consumption data a year prior to and a year after each of the tariff changes.

	2015 Tariff Period			2017 Tariff Period		
	Low	Medium	High	Low	Medium	High
All	133,735	92,304	37,708	170,209	94,708	34,806
Stable Consumption	99,512	28,329	16,473	124,701	30,719	16,666

within our specified time frame.

$$c = \begin{cases} Low, & \text{if } \bar{y}_i <= 15 \text{ kWh.} \\ Medium, & \text{if } 15 < \bar{y}_i <= 50 \text{ kWh} \\ High, & \text{if } \bar{y}_i > 50 \text{ kWh} \end{cases} \quad (2)$$

Stable consumption customers are defined as those with at least 80% of their monthly consumption falling within the same class in a 12-month period preceding the tariff change. This criterion ensures that our analysis considers customers with relatively stable consumption patterns, enabling a better understanding of the effects of tariff changes on stable consumption behaviors. Additionally, we only include customers who have been connected to the grid for more than a year, as they are considered "mature" consumers with a stable level of electricity consumption, as per (Fobi et al., 2018). This eliminates the impact of variability in consumption patterns exhibited by newly connected customers.

C. Temporal Segmentation

In order to gain insights into the evolution of residential electricity demand over time, we employ a data reshaping methodology akin to the one eudclidated in (Fobi et al., 2018). This method leverages the duration of each customer's grid connection to explore the typical alterations in electricity consumption patterns as the duration of grid connection increases. By employing this data reshaping technique, our objective is to furnish a more comprehensive understanding of the underlying dynamics governing residential electricity demand as it evolves over time.

IV. Results

A. Consumption patterns of Residential vs Non residential customers

In this section, we offer an in-depth analysis of the consumption behavior exhibited by both residential and non-residential customers within our dataset, irrespective of their grid connection date.

Between 2013 and 2019, the nation-wide electricity consumption showed an average annual growth of 4.6%. The non-residential sector experienced a 6.3% growth, while the residential sector recorded a more modest 3% growth. However, this growth falls below the target set by REG of 15%, essential for avoiding excess costs of generation and the subsequent necessity for government subsidies (REG, 2020).

It's crucial to acknowledge that our study excludes electricity consumption data from large-scale industries, which could significantly impact the aggregate electricity consumption growth.

Despite the growth in nation-wide annual consumption, Figure 6 illustrates a consistent decline in average monthly electricity consumption for both residential and non-residential customers. In January 2013, the average residential customer consumed about 45 kWh, while the average non-residential customer consumed about 170 kWh of electricity. By December 2019, the average residential customer's consumption had decreased by more than half to about 22 kWh, and the average non-residential customer's consumption had reduced by about 20% to 135 kWh. This highlights that fact that more lower consuming customers are getting connected to the grid.

Thanks to the prepaid nature of transactions, we can delve into the frequency with which customers make purchases. Our dataset provides insights into the time intervals between purchases and the quantity of electricity acquired in each transaction. In Kigali, residential and non-residential customers typically make purchases every 16 and 13 days on average, respectively. The average purchase amount for residential customers stands at 13 kWh, while non-residential customers acquire an average of 47 kWh per transaction.

Conversely, customers outside Kigali exhibit a distinct trend. Here, residential customers typically make purchases every 37 days on average, while non-residential customers do so every 20 days. Additionally, the average amount of electricity acquired per transaction is 7.2 kWh for residential customers and 21.2 kWh for non-residential customers.

Our dataset reveals that urban residential customers purchase electricity units for their accounts with a frequency 60% lower than their rural counterparts, and they consume 50% more electricity with each purchase. This combination shows that, on average, a residential customer outside Kigali consumes 71 kWh annually, compared to the 297 kWh consumed by an average residential customer in Kigali.

According to a USAID Power Africa Market Assessment report, rural electricity consumption in 2019 was 9.9 kWh per month, contrasting with 29.2 kWh per month in urban areas (USAID, 2019). These findings echo our observations from the transaction dataset, highlighting the significant disparity in electricity consumption between urban and rural areas in the country.

The GDP per capita in Kigali in 2017 was estimated at 2,865 USD, compared with 512 USD for non-Kigali districts (odi, 2020). When juxtaposing the GDP per capita figures in Kigali and outside Kigali with electricity consumption patterns, striking parallels emerge. The electricity consumption of Kigali residents is approximately four times higher than that of residents outside Kigali, mirroring the disparity in GDP per capita, where the GDP per capita in Kigali is about five times higher than that of residents outside of Kigali.

These pronounced correlations between GDP per capita and electricity consumption provide insights into how affordability significantly limits rural residents' access to and utilization of electricity as an energy source.

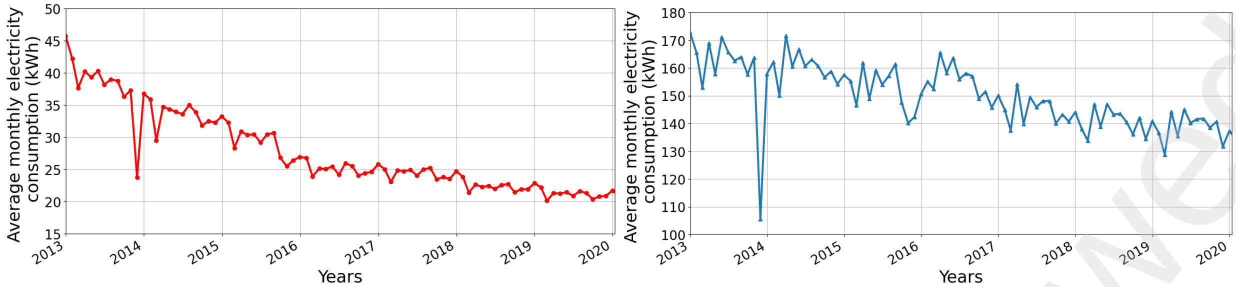
B. Consumption growth with time in Rwanda

As elucidated in Section II, the number of new customer connections in our transaction dataset is notably lower between 2016 and 2020 than the counts reported by official government sources. This disparity raises the possibility of bias within our dataset, wherein customers may be skewed towards wealthier or poorer segments of the country. This caveat serves as an important lens through which to interpret our findings in this section.

Our initial observation reveals that newly connected customers tend to stabilize at lower levels of consumption over time. Specifically, customers connected in 2019 and 2018 exhibit the lowest median consumption compared to older customers, as depicted in Figure 7. This discrepancy is more pronounced for residential customers than for non-residential ones. We observe two distinct clusters among residential customers, with consumption levels in the years 2017, 2018, and 2019 falling into the lower tier, while earlier years fall into the higher tier. Noticeably, residential consumption progressively decreases after each year except for customers connected in 2016. The anomalous nature of our 2016 data may stem from the divergence between new customer counts in our dataset and official government reports, creating a potentially biased sample set. However, without additional household data, we cannot confirm this hypothesis.

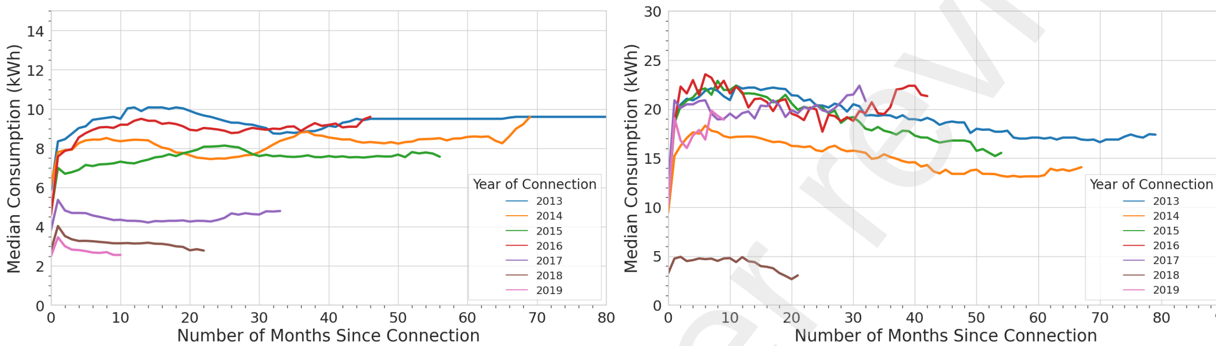
These consumption patterns align with similar observations made by (Fobi et al., 2018) and (Muhwezi et al., 2021) among Kenya's grid-connected residential and small commercial electricity consumers. However, consumption levels in Rwanda tend to be considerably lower. For instance, the median residential customer electrified in 2013 in Kenya plateaued at around 30 kWh/month, whereas the median residential Rwandan customer electrified in the same year plateaued at around 10 kWh/month. Although the absolute difference is only 20 kWh/month, the implications for energy providers vary significantly, as these customer groups may necessitate different electrification approaches.

Our second observation indicates that median electricity consumption among all cohorts remains relatively stable or



(a) Residential customers (b) Non-Residential customers

Fig. 6: Shows average monthly electricity consumption for REG's electricity customers.



(a) Residential customers (b) Non-Residential customers

Fig. 7: Shows median monthly electricity consumption for REG's electricity customers segmented by year in which they got connected to the grid.

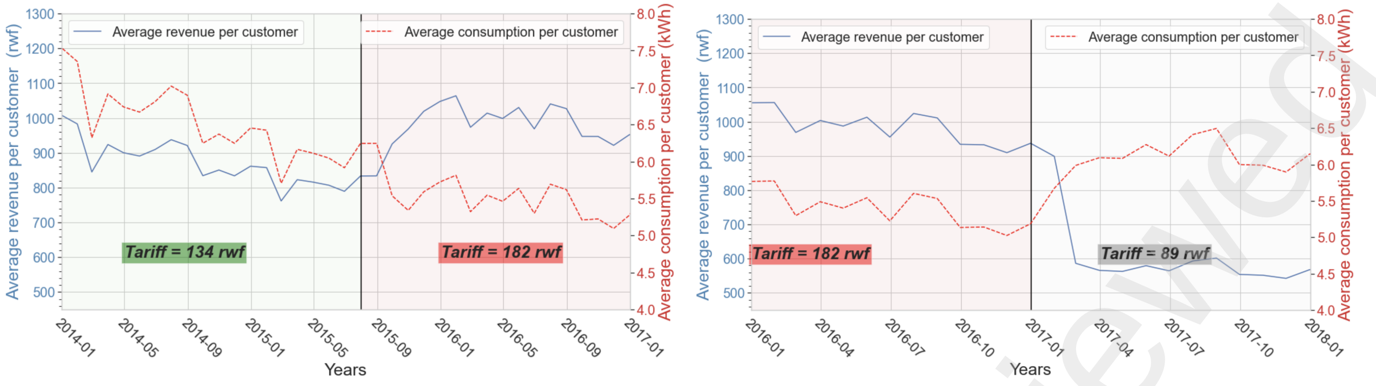
may even slightly decrease as consumers "mature" on the grid. This suggests that the nationwide growth in aggregated demand is not driven by existing customers increasing their electricity consumption but rather by the addition of new customers to the electricity grid. This underscores the notion that the Rwandan utility is catering to an expanding customer base whose consumption remains either static or undergoes minimal reduction. Such insight is invaluable for the utility in accurately identifying sources of consumption growth and estimating such growth for demand forecasting and infrastructure planning purposes.

C. Implications of Tariff Changes on Utility Revenues and Residential Consumption

Having seen how a typical REG customer's electricity demand evolves as a function of time spent on the grid, this section seeks to understand how demand evolves after residential tariff changes (in 2015 and 2017) and by extension how revenues remitted to the utility in the short term changed. To do this, we present the average monthly consumption per customer and the average monthly residential revenue per customer collected by REG after segmenting customers based on low-medium-high categories described in the methodology section.

As a result of the increased operating costs associated with running diesel power plants at Jabana 1 and 2, RURA increased the tariff for all customers by 35% from 134 rfw to 182 rfw (The NewTimes, 2015a). To determine the efficacy of this policy in achieving its aim of augmenting company revenue, the average monthly revenue per customer is analyzed both prior to and after the tariff change, as depicted in Figures 8a, 9a, and 10a. It is observed from these figures that the largest change in average monthly revenue per customer occurred in the medium category of residential customers, while less substantial changes in average monthly revenue per customer were observed for the low and high consumption categories. The most pronounced increase in revenue is observed in the initial three months following the implementation of the tariff change, after which the average monthly revenue per customer appears to level off. The actual percentage changes in the average monthly revenue per customer are documented in Table II.

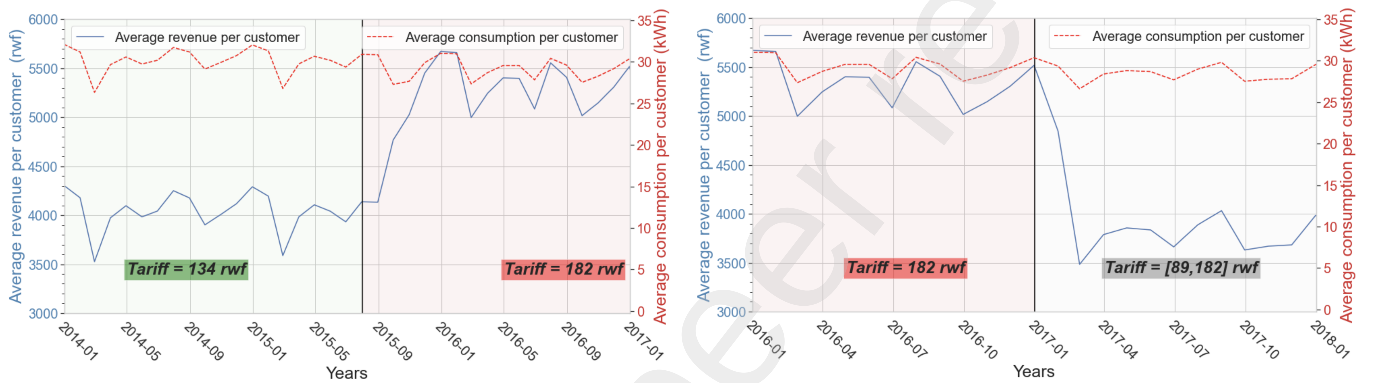
Given the 35% increase in electricity price, the corresponding per customer increase in average monthly revenue remitted to REG one year prior to and after the tariff change ranged between 10% and 31%. The largest per customer increase (31%) in average monthly revenue was observed in the medium consumption category which consists of customers consuming between 16 and 50 kWh/month. While the lowest increase in average monthly revenue (10%) was observed in the high consumption category. Although the high consumers displayed the lowest percent increase, they had the largest



(a) 2015 tariff hike on 99,512 customers

(b) 2017 tariff decrease on 124,701 customers

Fig. 8: Low category residential customers.



(a) 2015 tariff hike on 28,329 customers

(b) 2017 tariff change on 30,719 customers

Fig. 9: Medium category residential customers.

absolute increase of 2,606 rfw.

Conversely, declines in average customer consumption are observed across the three categories; low, medium and high, when comparing average consumption one year prior to and one year after the tariff change. The largest decline is observed with the high consumption category (17%) and the lowest with the medium consumption category (3%). However, it is worth noting a declining trend in consumption for the low consumption category before the 2015 tariff adjustment, suggesting the existence of factors beyond the tariff alteration contributing to this trend.

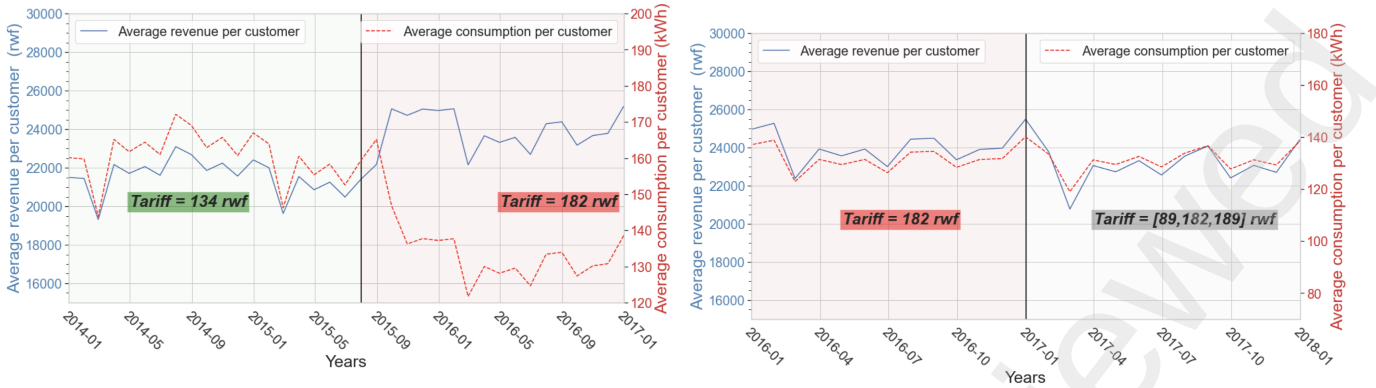
Interestingly, the medium consumption category has the highest increase in average monthly revenue per customer and the lowest decrease in average consumption after the tariff hike. One hypothesis could be that high consumers are more likely to possess a surplus of "discretionary power," which they can curtail in response to price hikes, whereas medium consumers may rely predominantly on electricity for essential energy needs, rendering them less capable of reducing their consumption.

Similar to our analysis of the 2015 tariff change, we examine how introduction of the block tariff in January 2017

TABLE II: Shows the average change in average monthly revenue per customer and average change in customer consumption for each of the Low, Medium and High categories one year before and after the 2015 tariff change.

	Low	Medium	High
Pre 2015 Tariff Change (rfw)	825	4,035	21,447
Post 2015 Tariff Change (rfw)	1004	5,294	24,053
Avg % Change in revenue	+21	+31	+10
Pre 2015 Tariff Change (kWh)	6.2	30.7	159
Post 2015 Tariff Change (kWh)	5.5	29.1	133
Avg % Change in consumption	-10	-3	-17

impacted the per-customer consumption and revenue remitted to REG. Figures 8b, 9b, and 10b show the average monthly revenue and consumption per customer pre and post the 2017 tariff change. We observe drops in average monthly revenue per customer for the low and medium categories, while the high category experienced a small drop in average monthly revenue per customer. Similar to the changes observed with the 2015 tariff change, this drop is experienced within the first



(a) 2015 tariff hike on 16,473 customers

(b) 2017 tariff change on 16,666

Fig. 10: High category residential customers

	Low	Medium	High
Pre 2017 Tariff Change (rfw)	978	5,283	23,978
Post 2017 Tariff Change (rfw)	600	3,869	23,032
Avg. % Change in revenue	-39	-27	-4
Pre 2017 Tariff Change (kWh)	5.3	29.0	132.0
Post 2017 Tariff Change (kWh)	6.1	28.4	131.0
Avg. % Change in consumption	+14	-1.8	-0.6

TABLE III: Shows the average revenue per customer collected by REG and average customer consumption for each of the Low, Medium and High categories one year before and after introduction of the block tariff in January of 2017

3 months of the 2017 tariff change.

Table III summaries the percentage changes in average monthly revenue per customer. From Table III, it is evident that the utility experienced a notable 39% decrease, on average, in monthly revenue per customer from customers in the low consumption category following the 2017 tariff adjustment. For those consuming below 15 kWh, this decrease resulted from a substantial 49% reduction in the tariff rate. In contrast, customers in the medium consumption category demonstrated a 27% reduction in average revenue remitted to the grid post-tariff change, which aligns with the expectation that these customers effectively benefit from a fixed discount applied to their electricity bills since they too benefit from the "lifeline" tariff. Conversely, customers in the high consumption category experienced only a modest 4% decrease in monthly revenue per customer.

The response in terms of consumption was most pronounced within the low consumption category, with their average customer consumption increasing by 14% from one year prior to the tariff change to one year afterward. In contrast, the medium and high consumption categories exhibited minimal adjustments in consumption following the 2017 tariff revision.

These findings suggest that customers in the medium consumption category display less sensitivity to price changes, as evidenced by their relatively unchanged consumption levels following both tariff adjustments. This observation holds significant implications for utility management and tariff regulation, indicating the potential to increase utility revenues with minimal decreases in electricity consumption among certain consumer segments. Such insights are pivotal for informing effective tariff policy implementation strategies.

V. Conclusion and Policy Implications

A. *Discussion and policy implications*

The progressive decrease in household electricity consumption as new customers are connected each year presents intriguing patterns that merit attention. Although our study does not establish direct causality, several explanations can be considered for this observed decline. Notably, the transition in 2017 to allow the connection fee of 56,000 RFW ($67 as of 2017) — previously a one-time upfront charge (ESRF, 2019; REG, 2022) — to be paid over time has likely played a pivotal role. This change could have both encouraged wider adoption of grid connections by lowering initial financial barriers and resulted in a higher effective per kWh cost for those benefiting from the deferred payment, compared to those connected earlier. This scenario offers a plausible context for the observed reduction in consumption among more recently connected households.

Previous research highlights that upfront costs seldom cover the full extent of utility investments (Golumbeanu and Barnes, 2013), and other studies (Nsabimana et al., 2022; Zhu et al., 2018), also underscore the role of income in shaping consumption behaviors, offering insights into the observed consumption patterns. Notably, recent and rural connections tend to represent lower-income households, consequently exhibiting reduced electricity consumption. Thus, while the country surmounts the challenge of extending grid access to every household, a new hurdle emerges: ensuring effective utilization of grid connections by households.

The implementation of a "lifeline" tariff has shown promise in incentivizing electricity use among lower-consumption households, particularly in rural areas where usage is typically minimal. However, the observation that higher consumption tiers also benefit from this tariff without a proportional increase in usage suggests an opportunity for tariff restructuring. Adjusting the block tariff could encourage greater consumption among lower-tier customers without significantly impacting the utility's revenue from higher-tier customers.

The Engel curve, illustrating the relationship between household income and the proportion of income spent on electricity, provides valuable insights. Generally, the Engel curve for electricity exhibits a U-shape, indicating that electricity is perceived as a necessity at lower income levels, with a higher income proportion allocated to it (Ahunov et al., 2022; Hasan and Mozumder, 2017; Nsabimana et al., 2022). As income increases, the proportion spent on electricity decreases as households prioritize other needs, until reaching a threshold, after which it rises again. The introduction of the lifeline tariff, while reducing the cost of electricity for lower-income households, did not result in a proportionate increase in consumption, possibly because these households prioritized other critical needs within their budget. This observation offers a nuanced understanding of the dynamics influencing consumption patterns, highlighting the complex interplay between affordability, priorities, and utility strategies in shaping electricity usage.

Additionally, our data indicates a plateau or decrease in consumption among earlier adopters, potentially influenced by the adoption of energy-efficient lighting and appliances. Over 800,000 incandescent bulbs have been replaced with more energy-efficient alternatives, alongside the growing use of energy-efficient screen-based appliances (Colenbrander et al., 2019; UNCC, 2014). These trends underscore the need for further exploration into the impact of energy efficiency on consumption patterns.

B. Overall Conclusion

Our detailed analysis of seven years of electricity consumption data reveals that newly connected households exhibit lower electricity consumption levels. Despite tariff reductions for customers in the lowest consumption tier, their overall expenditure on electricity decreased, indicating that reductions in tariffs did not lead to proportional increases in consumption. The median consumption levels of these lowest tier customers, consistently below 5 kWh per month, suggest their economically disadvantaged status. Indeed utility revenues from these customers went down and tariff reductions for the lowest tier also benefited those at higher consumption levels.

This pattern underscores the likelihood that economically vulnerable households prioritize other essential needs over increased electricity usage, even when tariffs are reduced. The specific contributions of efficiency improvements, such as LED lighting adoption and the preference for smartphones over televisions, to sustaining energy services with lower electricity consumption remain undetermined in our study.

A significant question in the academic and policy-making discourse is how governments can effectively utilize electricity access to foster consumption and enhance household welfare. Our findings highlight the Rwandan government's success in extending grid access to millions of households. However, they also suggest that achieving a meaningful increase in electricity consumption across these households may require a longer timeline than previously anticipated, echoing observations made by other researchers.

This study underscores the complex interplay between affordability, consumption behavior, and utility strategy in the context of expanding electricity access. It points to the need for tailored approaches that not only focus on connecting households to the grid but also on encouraging sustainable consumption patterns that contribute to the welfare of economically vulnerable populations.

VI. Acknowledgment

The authors of this study gratefully acknowledge the assistance of Tom Rwahama, Janvier Kabananiye, and Cyprien Habyarimana from the Rwanda Energy Group for facilitating our access to the customer transactions dataset. Their invaluable insights and constructive comments have played a pivotal role in enhancing the quality and depth of this study.

I am deeply grateful for the funding support extended by the Department of Earth and Environmental Engineering at Columbia University and the Rockefeller Foundation. This financial assistance has played a pivotal role in facilitating and enabling the progress of this work.

References

M. Ahunov, J. Kakhkharov, and P. Mozumder. Income and household energy consumption in a transition economy: the case of uzbekistan. *Energy*, 254:124085, 2022.

G. Bensch, J. Kluve, and J. Peters. Impacts of rural electrification in rwanda. *Journal of Development Effectiveness*, 3 (4):567–588, 2011.

Z. Boubakar, N. Williams, B. A. A. Diallo, and Y. Lare. Geotemporal analysis of electricity consumption growth in togo. In *2022 IEEE PES/IAS PowerAfrica*, pages 1–5, 2022. doi: 10.1109/PowerAfrica53997.2022.9905243.

S. Colenbrander, A. Sudmant, N. Chilundika, and A. Gouldson. The scope for low-carbon development in kigali, rwanda: An economic appraisal. *Sustainable Development*, 27(3):349–365, 2019.

ESRF. Lifting the burden of electricity subsidies, while expanding access. https://documents1.worldbank.org/curated/en/538521548274317451/pdf/133963-BRI-PUBLIC-23-1-2019-12-26-0-CountryBriefRwanda.pdf, 2019. Accessed: 2024-04-01.

S. Fobi, V. Deshpande, S. Ondiek, V. Modi, and J. Taneja. A longitudinal study of electricity consumption growth in kenya. *Energy Policy*, 123:569–578, 2018. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2018.08.065. URL https://www.sciencedirect.com/science/article/pii/S0301421518305949.

GCDL. Access to electricity vs. gdp per capita, 2020. URL https://ourworldindata.org/grapher/access-to-electricity-vs-gdp-per-capita. Accessed: 2024-03-06.

R. Golumbeanu and D. F. Barnes. Connection charges and electricity access in sub-saharan africa. *World Bank Policy Research Working Paper*, (6511), 2013.

S. A. Hasan and P. Mozumder. Income and energy use in bangladesh: A household level analysis. *Energy economics*, 65:115–126, 2017.

IDA. Second rwanda energy sector development policy financing. Technical Report PGD26, The World Bank, Washington, DC, Oct. 2018. URL https://documents1.worldbank.org/curated/en/370591542596427420/pdf/Rwanda-Second-Energy-Sector-Development-Policy-Financing-Project.pdf.

K. Jack and G. Smith. Charging ahead: Prepaid metering, electricity use, and utility revenue. *American Economic Journal: Applied Economics*, 12(2):134–168, 2020.

T. W. Klug, A. D. Beyene, T. H. Meles, M. A. Toman, S. Hassen, M. Hou, B. Klooss, A. Mekonnen, and M. Jeuland. A review of impacts of electricity tariff reform in africa. *Energy Policy*, 170:113226, 2022.

KPLC. Annual report and financial statements, 2015. URL https://kplc.co.ke/img/full/jSsYVq47rObE_KENYA%20POWER%20ANNUAL%20REPORT%202015%20-%20FOR%20WEB.pdf. Accessed: 2024-03-11.

L. Lenz, A. Munyehirwe, J. Peters, and M. Sievert. Does large-scale infrastructure investment alleviate poverty? impacts of rwanda's electricity access roll-out program. *World Development*, 89:88–110, 2017.

MININFRA. Backward looking joint sector review report for fy 2020/21, 2024. URL https://www.mininfra.gov.rw/index.php?eID=dumpFile&t=f&f=44920&token=5ebf3b18701d4e8d26b270ca2c9171b9a40a3efe. Accessed: 2024-03-01.

B. Muhwezi, N. J. Williams, and J. Taneja. Ingredients for growth: Examining electricity consumption and complementary infrastructure for small and medium enterprises in kenya. *Development Engineering*, 6:100072, 2021.

NISR Census. Main indicators: 5th rwanda population and housing census (phc), 2023. URL https://www.statistics.gov.rw/publication/main_indicators_2022. Accessed: 2023-03-06.

A. Nsabimana, B. J. Rukundo, A. Mukamugema, and J. C. Ngabitsinze. Residential energy demands in rwanda: Evidence from robust models. *Energy Policy*, 160:112665, 2022.

odi. Mayors dialogue on growth and solidarity: City profile: Kigali, rwanda. Technical report, ODI, 2020. URL http://www.jstor.org/stable/resrep51502.

G. Okoboi and J. Mawejje. Electricity peak demand in uganda: insights and foresight. *Energy, Sustainability and Society*, 6(1):1–16, 2016.

J. Peters and M. Sievert. Impacts of rural electrification revisited–the african context. *Journal of Development Effectiveness*, 8(3):327–345, 2016.

REG. Rwanda Electricity Distribution Master Plan. https://www.reg.rw/fileadmin/user_upload/Rwanda_Electricity_Distribution_Master_Plan.PDF, 2020. Accessed: 2022-06-24.

REG. Rwanda Energy Group Strategic Plan(2019-2024). https://www.reg.rw/fileadmin/user_upload/REG_Strategic_plan.pdf, 2020. Accessed: 2022-04-24.

REG. Reg new electricity connection policy. https://www.reg.rw/fileadmin/user_upload/RevisedNewConnectionPolicy__1_-75742.pdf, 2022. Accessed: 2022-06-26.

REG. History of REG. https://www.reg.rw/about-us/history/, 2024. Accessed: 2021-08-14.

RURA. RURA Strategic Plan (2013-2018). https://www.rura.rw/fileadmin/docs/RURA_Strategic_Plan_2013-2018.pdf, 2018. Accessed: 2021-08-14.

Statista. Number of households in kenya. https://kplc.co.ke/img/full/jSsYVq47rObE$_K ENYAAccessed: 2024-03-11$.

J. Taneja. If you build it, will they consume? key challenges for universal, reliable, and low-cost electricity delivery in kenya. *Center for Global Development Working Paper*, (491), 2018.

The NewTimes. REG chief explains increase in electricity tariff. https://www.newtimes.co.rw/section/read/191529, 2015a. Accessed: 2021-08-14.

The NewTimes. Needy families to benefit from lower power tariffs, 2015b. https://www.newtimes.co.rw/article/121516/News/needy-families-to-benefit-from-lower-power-tariffs,Accessed 2023-03-17.

UNCC. Rwanda switches on energy-efficient lighting. https://unfccc.int/news/rwanda-switches-on-energy-efficient-lighting, 2014. Accessed: 2024-03-01.

USAID. Off-grid solar market assessment rwanda. https://www.usaid.gov/sites/default/files/2022-05/PAOP-Rwanda-MarketAssessment-Final_508.pdf, 2019. Accessed: 2024-03-07.

USAID. Rural feeder roads improvement program. https://www.usaid.gov/sites/default/files/2023-04/Fact%20Sheet%20Rwanda%20Feeder%20Roads%20Development.pdf, 2024. Accessed: 2024-03-01.

World Bank. Access to electricity (% of population) - rwanda. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=RW, 2020. Accessed: 2022-04-24.

X. Zhu, L. Li, K. Zhou, X. Zhang, and S. Yang. A meta-analysis on the price elasticity and income elasticity of residential electricity demand. *Journal of Cleaner Production*, 201:169–177, 2018.