DETERMINANTS OF RESIDENTIAL ELECTRICITY CONSUMPTION EFFICIENCY IN NIGERIA'S NORTH-WEST REGION: EVIDENCE FROM A STOCHASTIC FRONTIER ANALYSIS

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Abstract
This study explores the socioeconomic, behavioral, and institutional determinants of residential electricity consumption efficiency in Nigeria's North-West region. where limited grid access, unreliable supply, and widespread non-metered billing arrangements such as fixed-rate and estimated tariffs shape household energy use. Using household level data for 168 respondents from the 2018 Multi-Tier Framework for Energy Access survey, the study estimates a stochastic frontier energy demand model with parameterized inefficiency and variance components. The model assesses the effects of behavioral, socioeconomic, and institutional factors on electricity consumption and technical efficiency. The results show that households on fixed or estimated billing consume significantly more electricity than prepaid-meter users, suggesting weaker price signals and lower incentives for conservation. Higher energy literacy, proxied by educational attainment, is associated with lower consumption and higher efficiency. The duration of appliance use, rather than the number of appliances owned, is the principal driver of higher consumption. Dwelling characteristics and the reliability of electricity supply also significantly affect efficiency. In addition, higher electricity prices and more consistent daily supply reduce inefficiency, indicating that tariff design and infrastructure reliability can serve as effective demand-side management instruments. The estimated mean technical efficiency is approximately 96 per cent; however, this should be interpreted as relative efficiency within a small and relatively homogeneous sample rather than as an absolute efficiency level, and it may be upwardly biased owing to the limited sample size and the exclusion of allocative and productive efficiency. By applying stochastic frontier analysis to an understudied Sub-Saharan African setting, the study extends the residential energy efficiency literature and demonstrates how institutional arrangements particularly metering systems and supply reliability interact with household characteristics to influence energy outcomes. The findings support context-sensitive policies that combine behavioral interventions, appropriate tariff structures, reliable supply, and technological measures to improve residential electricity efficiency in developing economies.
Keywords: Residential electricity consumption; technical efficiency; stochastic frontier analysis; prepaid metering.

1. Introduction

Estimated billing weakens the behavioral mechanism through which households respond to electricity prices. Unlike prepaid metering, which provides immediate usage information and links each additional unit consumed to an observable payment, estimated billing bases charges on prior consumption patterns or customer classifications rather than contemporaneous metered use. As a result, households have limited ability to monitor marginal consumption, assess the cost of specific appliances or usage practices, or verify the fairness of their bills. This weakens both price responsiveness and conservation incentives, particularly where supply is unreliable and households may already regard grid electricity as an imperfect or

contested service (Oseni & Pollitt, 2015; World Bank, 2026). The problem is empirically important in Nigeria: NERC reported that 53.85 per cent of registered electricity customers remained unmetered in the third quarter of 2024, leaving more than seven million customers dependent on estimated billing (NERC, 2024).

Although energy efficiency has been extensively studied in high-income countries using structural demand models (Filippini & Hunt, 2012; Houthakker et al., 1974), there remains a critical knowledge gap regarding the drivers of technical efficiency in electricity use within under-resourced, energy-constrained settings in Sub-Saharan Africa (Gillingham & Tsvetanov, 2018; Pachauri & Rao, 2013). Prior researches in developing economies had largely focused on access and affordability, with limited attention to how behavioral traits (e.g., energy literacy), socioeconomic characteristics (e.g., education, housing quality), and institutional factors (e.g., metering type, tariff design, and supply reliability) jointly shape efficiency outcomes at the household level (Mbeva & Sterner, 2021; Arouna & Dabrowski, 2020).

This study addresses this gap by analyzing the determinants of residential electricity consumption efficiency in Nigeria's North-West using a stochastic frontier energy demand model: a method increasingly validated for disentangling structural energy demand from technical inefficiency in both developed and developing contexts (Filippini & Greene, 2016; Kumbhakar et al., 2012). While evidence suggests that non-metered billing reduces price responsiveness and conservation incentives (Oseni & Pollitt, 2015; Adenikinju, 2005), and that appliance usage intensity not just ownership drives consumption (Arouna & Dabrowski, 2020), no study has yet applied frontier efficiency methods to household-level data in Nigeria's energy-constrained northern regions. Moreover, the role of supply reliability and electricity pricing as levers for improving efficiency remains underexplored in empirical work from Sub-Saharan Africa (Barnes et al., 2015; Mbeva et al., 2017).

Thus, this study seeks to answer the following question: What are the key behavioral, socioeconomic, and institutional determinants of technical efficiency in residential electricity consumption in Nigeria's North-West, and how do they interact within a context of unreliable supply and non-metered billing? Answering this question is essential for designing demand-side management strategies that integrate behavioral insights and institutional reforms not just infrastructure investment to improve efficiency in low-access settings (World Bank, 2020; Gillingham & Tsvetanov, 2018)

2. Literature Review

Residential electricity consumption in many developing regions remains inefficient, yet the factors underlying this inefficiency particularly in contexts marked by infrastructural deficits and weak institutional arrangements remain insufficiently understood. In Nigeria's North-West region, households face limited grid access, frequent and prolonged outages, and extensive reliance on non-metered billing arrangements, including fixed-rate and estimated tariffs (World Bank, 2024; National Bureau of Statistics [NBS], 2024). Nationally, an estimated 85.2 per cent of surveyed households were billed through estimated systems in 2024, while only 14.8 per cent used prepaid meters; grid-connected households also reported frequent supply interruptions (NBS, 2024). These institutional conditions weaken the link between actual consumption and payment, distort price signals, and reduce household accountability for electricity use (Oseni & Pollitt, 2015; World Bank, 2024). Consequently, residential consumption patterns may differ substantially from those observed in settings with

widespread metering and more reliable supply, where consumers face clearer marginal-price incentives and stronger feedback on usage (Adenikinju, 2005; NBS, 2024).

Studies on the determinants of residential electricity consumption efficiency have generally modelled the relationship in two interesting ways. A group of literature considers these determinants as having an indirect bearing on consumption efficiency through the frontier's demand equation and therefore modelled these factors within the efficient frontier. For example, while controlling for climatic and household characteristics, Filippini and Hunt (2012) studied the underlying energy efficiency level of households in the US and found that efficiency level averaged 89% across the states. Similarly, Alberini and Filippini (2015) estimate the transient and persistent inefficiency in residential electricity consumption of US households and found both types of inefficiency to average 10% and 17% respectively. Blasch, Boogen, Filippini and Kumar (2017) explored the effect of energy-related financial literacy on the level of transient and persistent inefficiency among Swiss households and found an average inefficiency of 11% and 22% respectively.
One notable shortfall with this group of literature is that they fail to explicitly model factors that directly determine households' electricity consumption inefficiency and are therefore unable to measure the contributory effect of each determinant. Consequently, efficiency scores from these studies are suspiciously noisy since they fail to control for systemic deviation from the frontier.

A second group of literature attempt to address the aforementioned challenge by explicitly modelling factors that directly influence residential energy efficiency in either the mean or variance equation of a realization. Underlining this approach is the idea that systematic patterns in how people deviate from the frontier are not explained by the frontier itself, but manifest in model heterogeneities via the determinants. This therefore helps to address issues of heterogeneities and heteroscedasticity in addition to adequately right-scaling the estimated frontier. Through this modelling, internal factors such as households' perception and bounded rationality have extensively been studied and consistently proven to significantly explain residential energy consumption efficiency. For example, across 7000 Chinese households, Broadstock, Li and Zhang (2016) show that perception about the environment significantly influenced their energy efficiency level. In a behavioral study, Boogen, Cattaneo, Filippini and Obrist (2021) found that households with strong cognitive investment literacy were 0.14% more energy efficient compared to those with lower cognitive abilities. Similarly, Filippini, Kumar and Srinivasan (2019) reveal that higher energy-related financial literacy correlated with higher likelihood for Nepalis households to replace inefficient appliance. In addition, Blasch, Filippini and Kumar (2016) showed that investment literacy and energy information especially when presented in monetary terms significantly determine efficiency level of households in urban Switzerland.

Other households' behaviors such as standby consumption and absenteeism have also been studied. Boogen (2017) provide pioneering evidence showing that Swiss households that do not practice standby consumption were more efficient than those who did. In a different study, Blasch et al. (2017) confirmed that Swiss households who switch off appliance when not in use, and wash cloths at low temperatures were significantly more energy efficient than households that do not practice this efficient behavior. Likewise, Boogen et al. (2021) found households across Italy, Netherlands, and Switzerland that were more frequently absent from home to have higher electricity utilization level than those that were more frequently on

ground. Similar finding emerged in a study of 2000 German households (Andor, Bernstein & Sommer, 2021).

Aside internal barriers to energy efficient practice, households equally face enormous external constraints. These constraints are largely outside their control and mostly determined by institutional settings. Though factors constituting this constraint have widely been studied, their effects on residential efficiency have nonetheless been mixed. Households' income, for instance, have produced divergent results. While Andor et al. (2021) showed that higher income among German households lead to significant increase in energy consumption efficiency, Boogen et al. (2021) concluded that it was insignificant in determining household efficiency across Italy, Netherlands, and Switzerland. Broadstock et al. (2016) surprisingly found wealthier household living in cities to be inefficient compared to those living in villages and town; an evidence that questions the energy ladder hypothesis. Other factors such as household education and residency status have nonetheless produced consistent results. More educated households are both able to easily compute the lifetime cost of investing in efficient appliance and also affordably make their purchase. Studies have therefore established the positive effect of households' education on their level of efficiency (see Boogen et al. 2021; Broadstock et al. 2016; Broadstock & Li, 2016). Evidence pointing to the relative inefficiency of tenants compared to landlords have theoretically been justified through the split problem (Andor et al. 2021; Boogen et al. 2021; Broadstock & Zhang, 2016).

Household size, composition, head, and house type and age have also been found to influence the level of residential efficiency (see Broadstock & Li, 2016; Otsuka, 2017). Furthermore, household's appliance stock and composing, their cooking fuel and water source as well as underlying illness have also been explored (see Weyman-Jones, Boucinha & Inácio, 2015). Their effects have however produced mixed result.

A small but growing body of study is evolving within the latter group of work. This new strand examines the effect of energy demand management on residential efficiency level. Energy efficiency initiatives and utility load management strategies are veritable tools for influencing household consumption efficiency and therefore remain an important determinant of residential efficiency level. For example, Filippini et al. (2014) found that efficiency polices such as financial incentive and efficiency standards significantly reduce residential inefficiency by 0.47% and 0.35% respectively among EU-27 countries. Weyman-Jones et al. (2015) concluded that the Portuguese Ministry of Economy's distribution of efficient light bulbs yielded the expected energy saving especially when the effect of temperature is accounted for. Similarly, Saussay, Saheb and Quirion (2012) showed that building codes enacted across seven European countries significantly increased their level of efficiency in residential space heating. Other studies on utility load management strategies such as load shedding, rationing, and client classification have interestingly found them to influence residential energy efficiency (see Boogen, 2017; Boogen et al., 2021; Broadstock et al., 2016; Weyman-Jones et al., 2015).

Collectively, these studies generally point to the crucial role of behavioral and socioeconomic characteristic in determining residential level of electricity consumption efficiency. These factors are therefore potential policy tool for targeting cost-effective efficiency improvement among households. However, the evidence available so far are mostly for advanced economy with the exception of Filippini, Kumar, and Srinivasan (2019). In addition, the level of residential efficiency and the effect of other utility load management strategies that are prevalent in developing countries have not received sufficient scholarly attention. This study therefore aims to fill this gap by providing new insight using the Nigerian case study.

3. Methodology

Energy is an important input in household production function. Microeconomic theory of production hypothesizes the demand for energy as derived from the services it enables household to enjoy. Such services typically include lightening, cooking, heating and cooling. The demand also depends on techno-economic factors such as the stock of appliance as well as other household characteristics. Expectedly, households would seek to combine energy with other inputs to produce outputs in such a way that minimizes the quantity of inputs used to produce the given level of output. Specifically, it seeks to use energy more efficiently in order to reduce wastage and minimize operating cost. Several models have thankfully been developed within energy economics to determine the level of households' consumption efficiency. The two most common models are Data Envelopment Analysis (DEA) and stochastic frontier model. DEA is a non-parametric model that uses linear programming to construct an efficient frontier while benchmarking independent decision-making units against the constructed frontier to determine their relative efficiency levels. Though this model is widely adopted within and outside energy economics, it nonetheless suffers serious setbacks. Firstly, because it is a non-parametric model, it notably does not differentiate between shocks and lucks from pure economic inefficiencies. Secondly, it has proven to have weak discriminating power in addition to its inability to suitably control for factors explaining observed efficiency of decision-making units.

Stochastic frontier models have widely dominated efficiency analysis partly because they address setbacks identified within the DEA, and also because of their flexibility and analytical prowess. Unlike the DEA, stochastic frontier models are parametric models that uses Maximum Likelihood to determine units' efficiency, and suitably controls for heterogeneities and heteroscedasticities. Depending on the type of analysis and data availability, three functional forms of the model are often used in empirical works. These versions consist of the energy distance function, input requirement function, and energy demand function. Each function is credited with peculiar relevance especially considering the strength of their relative theoretical foundations. Filippini and Hunt (2012) however noted that the energy demand function impressively combines insight from two broad literatures consisting of energy demand and energy efficiency studies. Furthermore, this function has been shown to approximate productive efficiency particularly when modelled within a cobb-Douglas production framework (Filippini, Hunt, & Zorić, 2014). For these reasons, this study adopts the energy demand function to determine household energy consumption efficiency level.

Underpinning the energy demand function is the idea that the demand for energy is derived, but depends on techno-economic and specific household characteristics. Functionally, the relationship between energy demand and its corresponding determinants is defined as

$$E_i = f(Mfx_i, Mst_i, Pql_i, Prb_i, Sqt_i, Sus_i, Edu_i, Dwl_i) \quad 1$$

where the function implies that a household energy consumption level E_i, depends on factors such as whether it is charged a fixed (Mfx_i) or estimated rate (Mst_i), the quality (Pql_i) and reliability (Prb_i) of its power supply, the quantity (Sqt_i) and use-hours (Sus_i) of appliance stock, its dwelling type (Dwl_i) as well as level of energy literacy (Edu_i). With a stochastic frontier model, it is possible to define how energy as an input can efficiently be utilized while ensuring the required energy services to households. Frontier equations are common place where energy is modelled as a linear function of selected covariates accompanied by two uncorrelated error terms. Equation 2 defines the stochastic frontier equation of a typical energy demand function.

$$lnE_i = \alpha + Z_i'\beta + (v_i + \mu_i) \quad 2$$

lnE_i is natural log of household energy consumption, α and β are time-invariant coefficients representing frontier parameters to be estimated. Z_i' Is a vector of exogenous covariates determining households' level of energy consumption, v_i is by assumption a gaussian white noise that captures errors from model misspecification and random shocks to the efficient frontier. μ_i is mostly the focus of efficiency analysis. By construction, it is a half-normal error term that represent households' inefficiencies in energy consumption. It equally assumes other forms of distributions such as a normal-truncated-normal, gamma, and exponential distribution. While the choice of distribution depends on computational convenience and the nature of data at hand, there are implications for result consistency across distributions.

A major setback of stochastic frontier models is that they assume homoscedasticity. By controlling for additional covariates, it is possible to address this challenge while also exploring insights on factors that explain households' efficiency levels. A starting point is to parameterize the mean equation of the truncated-normal term and the variance of the idiosyncratic term as

$$u_i \sim \mathcal{N}^+(\mu, \sigma_{ui}^2), \quad \mu_i = \exp(\boldsymbol{h}_i'\phi) \quad 3$$

$$v_i \sim \mathcal{N}(0, \sigma_{vi}^2), \quad \sigma_{vi}^2 = \exp(\boldsymbol{\psi}_i'\eta) \quad 4$$

u_i is a realization from a truncated normal random variable, and v_i is realized from an idiosyncratic variance component. Both equation 3 and 4 are parameterized with exogenous variables such that $\boldsymbol{h}_i'$ and $\boldsymbol{\psi}_i'$ are the vectors of those variables, and ϕ and η are their respective parameters to be estimated. Using the Jondrow et al. (1982) command, the mean inefficiency term can be predicted as

$$Eff = \exp(-\hat{u}) = e^{-\hat{u}} \quad 5$$

where Eff is the average efficiency level of households within the sample, and $e^{-\hat{u}}$ is an exponential function of a truncated normal error.

3.1 Data Sources

This study uses data from the multi-Tier framework for measuring energy access, a comprehensive survey data on energy access covering the north-west geo-political zone of Nigeria. States captured within this survey include Kaduna, Kano, Kebbi, Jigawa, Sokoto, and Zamfara and constitute 3,696 household spread across 264 Enumeration Areas. The survey was conducted in 2018 and funded by Energy Sector Management Assistance Program (ESMAP) and Scaling up Renewable Energy Program (SREP) but administered through the World Bank. It collected comprehensive data on the access, quality, and reliability of household energy profile. However, because most households within the north-west region do not have access to grid supply or are unmetered, data on energy consumption and energy prices were unfortunately scanty. Only 168 households reported data on these variables, constraining this study to a small sample.

4. Result and Discussion

4.1 Descriptive statistics

Table 1 summarizes the descriptive statistics of households in the sample. The result reveals that on average, households consume 939kwh of electricity per month and pay N5,850 as monthly electricity bill. In addition, households have an average of 7 persons residing within the dwelling of Nigeria, these numbers are not surprising. Regarding power supply, more than 70% considered their power supply to be of good quality, causing no damage to their appliances. Furthermore, this power was available for an average period of 116 hours per week, though with notably large standard deviation.

Table 1: Summary Statistics of Sample Household

Variable	Mean	Std. Dev.	Min	Max
Household Electricity Billing System (Dummy)				
Fixed rate	0.780	0.416	0	1
Estimated billing	0.119	0.325	0	1
Monthly Electricity Consumption Profile				
Electricity consumption (KWh)	939.135	4578.019	3.3	53664
Electricity price (Naira)	5,850.149	39117.83	103	50,886
Household Power Supply Profile				
Daily supply (Hours)	5.133	3.947	0	20
Weekly supply (Hours)	116.68	58.512	0	136
Damage to appliance (Dummy)	0.768	0.424	0	1
Household Electrical Appliance Profile				
Stock	16.387	13.299	1	93
Daily usage hours	22.679	12.864	2	70
Household Dwelling characteristics				
Multiple dwelling (Dummy)	0.548	0.499	0	1
Number of Rooms	4.357	2.763	1	17
Household size	7.452	4.688	1	25

Source: MTEA (2018)

Mean appliance stocks used in a household is around 16. This stocks however ranges from small appliances such as rechargeable touch lights, phone charges, and light bulbs, to big appliances such as washing machines, ovens, and pressing irons. Cumulatively, households report using these appliances for an average of 23 hours per day. Though about 78% of sample household use a fixed-rate metering system where a flat rate is charged per month regardless of the power consumed. Also, about 12% of households are on estimated billing while roughly 10% use prepaid. This differences in metering system can have important implications for energy consumption as well as management. This possibility is investigated in the next section.

4.2 Result Discussion

Table 2 present results from the estimated energy demand equation, and the parameterized mean and variance function. Two distributional assumptions regarding the inefficiency term were made. While the H-ND assumes that the inefficiency term follows a half-normal distribution, the T-ND rather assumes it follows a truncated normal distribution. Though these assumptions can have implications for the result, they are nonetheless relevant for understanding and choosing a robust model. Surprisingly, both models produced similar parameters as well as average efficiency in this case.

Factors such as households' metering system appear to positively and significantly influence the level of their energy consumption. For instance, compared to households using prepaid billing system, those using fixed and estimated billing respectively consume 0.56% and 0.88% more electricity on average. This is unstartling because households on fixed and estimated billing do not pay the real price of what they consume and therefore have no incentive to be mindful of their consumption or efficiency. Also, compared to households living in single dwelling, those living in multiple dwelling consume 0.38% less electricity. Multiple dwelling efficiently allows fewer energy appliance to deliver required energy services. Fewer light bulbs, for example, are needed to illuminate the constituent apartments compared to when each apartment is a stand-alone. In addition, there could also be room for sharing certain appliances within the dwelling, thus limiting the need for each household to own one. Though the result suggests that households' stock of appliances increases the consumption of electricity, this result appear not to be statistically significant. Rather, the average daily hours for which these appliances are used seems to be what significantly influences their energy consumption. Such that, a percentage increase in the daily use-hours of these appliances result in a 0.011% increase in their level of energy consumption.

Households' energy literacy level importantly determines their energy consumption profile. Proxied by average level of highest educational qualification, the result shows that energy literacy is associated with lower level of households' electricity consumption. This suggests that households with no or basic education would consume more electricity than those with secondary and tertiary education. Specifically, a percentage increase in average level of highest educational qualification result in a 0.79% decrease in household electricity demand. This result corroborates studies establishing the strong nexus between energy literacy and energy consumption efficiency.

Table 2: Estimated Parameters of Energy Demand Frontier Model

Frontier Parameters	H-ND	T-ND
Mfx	0.5602***(0.043)	0.5502***(0.141)
Mst	0.8818***(0.158)	0.8248***(0.128)
Pql	0.1123**(0.045)	0.1025(0.129)
Dwl	-0.3758***(0.016)	-0.3732***(0.027)
Edu	-0.7876***(0.064)	-0.8153**(0.342)
Sqt	0.0171(0.021)	0.0187(0.034)
Sus	0.0108***(0.002)	0.0110**(0.005)
Prb^w	0.0030***(0.000)	0.0031***(0.000)
C	6.4565***(0.180)	6.5253***(1.051)
Parametrized Mean	μ_i	μ_i^+
Prc	-1.1739**(0.499)	-1.6306***(0.473)
Prb^d	-0.4125*(0.228)	-0.2541(0.292)
C	9.7372**(3.940)	12.0533***(3.622)
Parametrized Variance	σ_{vi}^2	σ_{vi}^{2+}
Rms	-6.9882(6.967)	-9.2858(6.622)
Hsz	-8.4523**(3.301)	-10.0990***(3.468)
C	12.6478(8.104)	15.7198**(7.979)
Mean Efficiency	0.96	0.97
Log likelihood	-52.1163	-46.2674

Source: Author's computation using Stata

Underpinning the nexus is the argument that energy literate households who are consciously aware of their energy consumption level, appliance efficiency rating as well as their lifetime cost, are more likely to be rational in making energy consumption related choices as compared to households lacking such knowledge.

One interesting finding of this study is the result of how electricity supply affects its consumption. The effect of electricity quality and reliability on electricity demand have

received minimal attention, with very little currently known. The quality of power supply, proxied by voltage fluctuation resulting in appliance damage, significantly affect the level of households' electricity consumption. This is equally true for a reliable electricity supply as measured by weekly average hours of power supply. Respectively, a quality and reliable power supply result on average in a 0.112% and 0.003% increase in household demand for electricity. Because most households in Nigeria are considered energy poor, attempts to improve power supply either by enhancing its quality or reliability would expectedly result in higher energy consumption. This result therefore reinforces this possibility.

While the estimated parameters of the energy demand frontier are seldomly used to infer the determinants of household efficiency level, this inference may potentially be misleading. This is because factors that appear to increase energy consumption may not necessarily be associated with households' efficiency and vice versa. Understanding these efficiency-drivers was aided by controlling for two additional variables in the truncated mean equation.

Firstly, the result confirms that energy prices significantly reduce households' electricity consumption inefficiency. Specifically, a percentage increase in energy prices results in a more than proportionate decrease in households' consumption inefficiencies by 1.173%. Typically, as energy prices increases, households, especially those on flexible metering system, would respond by cutting down power consumption through the use of more efficient appliance or less appliance stocks. In turn, these adjustments ultimately translate into reduced consumption inefficiency within the household. Similarly, average daily power supply, a proxy for power supply reliability, appear to equally reduce households' inefficiency level. A percentage increase in daily power supply is associated with a 0.413% decrease in household consumption inefficiency. This suggest that as power supply becomes stabler, households are more likely to be cautious of their consumption because they can more often remember to switch off appliance when not in use or when no one is at home. However, this practice is improbable when power is frequently restored at mid-night or day time when most families are out of home while appliances remain plugged-in from earlier usage.

Differences in households' level of consumption efficiency can also be driven systematically by factors such as households' size and number of rooms in dwelling. Both factors were controlled for in the idiosyncratic variance equation. Unlike the number of rooms in household dwelling, number of persons living within households significantly explain systematic differences in observed efficiency levels. Because this variable appears significant, it remains instrumental to right-scaling the efficiency frontier as well as ensuring an accurate efficiency estimate. From the two competing models presented in the table, average efficiency appears to vary slightly across both models. While it averaged 0.96 in the H-ND model, it is 0.97 in the T-ND model. However, because the H-ND model has the highest maximum log likelihood value, it is the preferred model of this study.

An important caveat is exercised in generalizing this result. Stochastic frontier model in particular, and efficiency measurement models in general, are based on the idea of relative efficiency. This means that efficiency levels are obtained based on the number, nature, and feature of independent units constituting the sample used for analysis. As these factors changes, so would the estimated efficiency expectedly change. Consequently, these factors provide justification for the high efficiency score reported in this study. Firstly, because comprehensive data were only available for 169 households, the number of independent units considered are relatively small, and thus efficiency benchmark is low. Secondly, constrained

by data, other aspect of households' efficiency such as allocative and productive efficiency were not examined, thus limiting the analysis to technical efficiency alone. When these efficiency dimensions are considered, households' efficiency level would expectedly be lower than currently observed. Lastly, with larger sample comes more heterogeneity which in turn competitively benchmarks units against constructed efficient frontier. Collectively, these cautions suggest that an efficiency level of 0.96 is on the high side and reflect relative rather than absolute efficiency in household energy consumption.
To the extent that households' level of energy literacy, appliance stock, and dwelling type significantly influence electricity consumption as well as its efficiency, this study corroborates the findings of Andor et al. (2021), Broadstock and Li (2016), and Weyman-Jones et al. (2015). Also, the results are in line with the works of Boogen et al. (2021), Boogen (2017) and Broadstock et al. (2016) which show the significance of utility load management strategies such as load shedding and rationing on household electricity consumption.

5. Conclusion and Recommendations

5.1 Conclusion

This study advances understanding of residential electricity consumption efficiency in an under-researched and energy-constrained setting: Nigeria's North-West region, where limited grid access, erratic supply, and widespread reliance on non-metered (e.g., fixed-rate or estimated) billing are prevalent. Using a stochastic frontier energy demand model with parameterized inefficiency and variance components, we analyze household-level technical efficiency and the influence of behavioral, socioeconomic, and institutional factors on electricity use. The analysis draws on a unique sample of 168 households from the 2018 Multi-Tier Framework for Energy Access survey.

Key findings indicate that households subjected to fixed or estimated billing consume significantly more electricity than those using prepaid meters, reflecting diminished price responsiveness and weaker conservation incentives. Higher energy literacy proxied by educational attainment is strongly associated with both lower consumption and greater technical efficiency. Notably, the duration of appliance use (rather than the number of appliances owned) is a significant driver of electricity consumption. Additionally, dwelling type and the reliability of power supply significantly influence efficiency outcomes. Crucially, higher electricity prices and more consistent daily supply are linked to lower inefficiency, underscoring the potential of well-structured pricing mechanisms and reliable infrastructure as effective demand-side management tools.

The estimated average technical efficiency is approximately 96%. However, this figure should be interpreted with caution: it reflects relative efficiency within a small and relatively homogeneous sample and does not account for allocative or productive efficiency. The estimate may also be upwardly biased due to sample limitations. Nevertheless, by applying stochastic frontier analysis to a context that has received scant attention in the Sub-Saharan African energy literature, this study fills a critical geographic and methodological gap. It demonstrates how institutional features especially metering arrangements and supply reliability interact with household characteristics to shape energy efficiency in settings marked by infrastructural and institutional constraints. These insights offer a foundation for designing targeted, context-sensitive policies that integrate behavioral and institutional levers alongside technological interventions to improve residential electricity efficiency in developing economies.

5.2 Recommendations

Informed by the study's empirical results, the following evidence-based recommendations are proposed to enhance residential electricity consumption efficiency in Nigeria's North-West region and comparable energy-constrained settings

1. Accelerate the Deployment of Prepaid Metering: Regulatory authorities and distribution companies should prioritize the replacement of fixed and estimated billing systems with prepaid meters. Such systems enhance price transparency, strengthen consumer responsiveness to tariffs, and provide direct incentives for efficient electricity use.

2. Enhance Energy Literacy Through Targeted Education: Public and community-based programs that improve household understanding of energy consumption, particularly in underserved regions should be expanded. Greater energy literacy empowers consumers to make informed decisions, reduce wasteful practices, and optimize appliance usage.

3. Invest in Grid Reliability: Improving the consistency of daily electricity supply is not only essential for service quality but also conducive to consumption efficiency. Reliable supply enables households to plan and manage their usage more effectively, thereby reducing inefficiency.

4. Design Equitable and Efficient Tariff Structures: Electricity tariffs should better reflect the marginal cost of supply while incorporating pro-poor safeguards. Where feasible, time-of-use or dynamic pricing supported by smart metering and consumer education can further promote efficient consumption patterns.

5. Adopt Integrated, Multi-Dimensional Policy Approaches: Energy efficiency strategies in low-capacity markets must move beyond technology-centric solutions (e.g., distributing efficient appliances) to incorporate institutional reforms, behavioral insights, and infrastructure improvements. A synergistic approach that aligns metering, pricing, reliability, and education is more likely to yield durable efficiency gains.

6. Strengthen Data Collection and Research Capacity: Future studies should utilize larger, more diverse, and nationally representative samples across Nigeria's geopolitical zones. Such efforts will improve the robustness and generalizability of efficiency estimates and support evidence-based policymaking.
7.

Collectively, these recommendations offer a pathway for Nigeria and comparable contexts in Sub-Saharan Africa to build more efficient, equitable, and resilient residential electricity systems that account for the complex interplay of infrastructure, institutions, and human behavior.

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