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Impact of household electricity theft and unaffordability on electricity security: A case of Uganda

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ABSTRACT

Renewable energy sources (RES) dominance in Uganda's electricity mix is challenged by affordability and theft. To assess electricity affordability, the study proposed a probabilistic method to quantify the households into different electricity categories for both urban and rural areas. Alternative electricity billing schemes based on Scenarios A to D for the households to enhance legal connection and consumption of electricity were proposed. The study established that the utility registers the highest electricity theft losses in rural households. The monthly utility revenue collected in urban areas was about 2.9 times that collected in rural areas because of the higher number of legally connected households with a monthly consumption of 1.5 times than that of rural households. From the monthly income spendable on electricity, rural and urban households could only afford 25.07 kWh and 38.29 kWh, respectively, which are less than the average household electricity consumption for Uganda. Also, the initial connection fee to the power grid is very high for the households to afford it in a single down payment. Of the proposed alternative billing schemes, Scenario B and Scenario D yield the least monthly utility revenue collected for the urban and rural households, respectively.

1. Introduction

Electricity is a vital component of social prosperity and economic inclusion. A direct implication is that for end-users to value and productively utilise electricity, it must be available, accessible, affordable, and reliable. These attributes, combined, characterise what literature describes as electricity security. Studies (Neelawela et al., 2019b; Sarhan et al., 2021; Larsen et al., 2017) enlist affordability as one of the fundamental dimensions of electricity security. When electricity is affordable, individuals are likely to meet their energy needs without compromising the quantity and quality of electricity supply. Conversely, when electricity is expensive and unaffordable, individuals are likely to engage in furtive approaches such as electricity theft, to access and use electricity. Theft of electric power threatens electricity security on three levels (i) cause supply disruptions to the entire electricity system through load instabilities, (ii) impose economic losses to the utilities company and may discourage further energy investments, and (iii) reduce the quality of electricity supply to legitimate consumers.

Policies within the sustainable development framework target, among others, the achievement of universal access to energy by 2030. In the Sub Saharan Africa (SSA), this aspiration will necessitate availing affordable and reliable energy to over 645 million people region through grid connection and generation decentralization, i.e., by implementing mini-grids and/or off-grid systems (Africa Progress Panel, 2015; Mukisa et al., 2021). Currently, Africa's energy systems are characterised by inequity, unreliable and inefficiency services. There is an urgent need for development of innovative business models that can guarantee access to reliable and affordable energy by people whose daily income is less than $ 2.50 (Africa Progress Panel, 2015; Mukisa et al., 2021). While Africa has vast technical potential of both conventional and renewable energy resources, the SSA region is characterized by very low access to electricity, and is globally qualified as the least electrified region (Mukisa et al., 2021; Blimpo and Cosgrove-Davies, 2019). Besides low electricity access rates, electricity deficits in SSA manifest as limited consumption, widespread unreliability, restrictive tariffs, network distribution losses, and financial shortfalls by utilities (Mukisa et al., 2021; Blimpo and Cosgrove-Davies, 2019; Jiménez et al., 2014).

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Nomenclature

ECM	Error Correction Model
EPBS	Electricity Prepayment Billing System
GDP	Gross Domestic Product
GSM	Grid Smart Metering
IEA	International energy Agency
MSE	Medium and Small Enterprise
PV	Photovoltaic
RES	Renewable Energy Sources
SE4All	Sustainable energy for All
SSA	Sub-Saharan Africa
C_f	Initial connection fee
C_i	Initial connection cost to power grid
E_p	Utility bill for a partial electricity theft
G_a	Utility loss to all-electricity stealing household
G_p	Utility registered pecuniary loss from a partial electricity stealing household
HH_a	All-electricity stealing household
HH_p	Partial electricity stealing household
I_f	Inspection fee
I_m	Monthly household income
L_a	Total utility revenue losses to the illegally connected all-electricity stealing households
L_p	Total utility revenue losses to the legally connected but partial electricity stealing customers
R_g	Total utility revenue collection
SE_m	Monthly household expenditure on electricity
T_a	Consumed electricity by all-electricity stealing household
T_p	Concealed electricity by partial electricity stealing household
$t_{c,u}$	Duration to afford the initial connection cost
HH_g	Genuine electricity household
HH_p	Partial electricity stealing household
C_r	Rural household monthly electricity consumption
N_a	Not-connected household but steal electricity
$p(HH_{ng,r})$	Probabilities that a household in rural areas is not-connected
$p(HH_{a,u})$	Probability of electricity theft for not-connected urban household
$p(HH_{a,r})$	Probability of electricity theft for not-connected rural household
$p(HH_{p,r})$	Probability of electricity theft for connected rural household
$p(HH_{ng,u})$	Probabilities that a household in urban areas is not-connected
$p(HH_{cg,r})$	Probabilities that a household in rural areas is connected
$N_{a'}$	Not-connected households that also don't steal electricity
C_u	Urban household monthly electricity consumption
N_p	Connected households that partially steal electricity
N_r	Sample size of urban households
N_u	Sample size of urban households
E_g	Household's actual expenditure on consumed electricity
$p(HH_{p,u})$	Probability of electricity theft for connected urban household
$p(HH_{cg,u})$	Probabilities that a household in urban areas is connected
α	Domestic electricity tariff rate
V_c	Value added tax rate
M_s	Standard monthly service fee
X	Electricity paid for by a partial electricity stealing household

From the perspective of security of electricity supply, the electricity utilities in SSA continue to confront the challenge of persistent high losses. A utility in developing countries is considered to be well performing if its total loss level is 10% or below (Lawaetz, 2021). In developed countries, power losses are mainly technical losses, while in developing countries, power losses are mainly non-technical losses. The higher losses in developing countries are often an indication of poor management, corruption, and/or shortage of resources and expertise in addressing the losses (Lawaetz, 2021). In several developing countries, electricity theft is routinely cited as the primary cause of non-technical losses. Non-technical losses refer to electricity effectively delivered by a supplier but not paid for by the users, resulting in direct financial losses for the utility, and these are attributed to theft, fraud, unmetered supply, and mismanagement (Jiménez et al., 2014). These non-technical losses affect the revenue collection of the utility as well as the country's gross domestic product (GDP). Averagely, hidden costs of distribution losses account for about 0.5% of a country's GDP in SSA region (Never, 2015). Dishonest people either steal electricity directly by illegally tapping on distribution lines or bribe utility employees to avoid risks of being detected and/or convicted due to overdue electricity consumption (Jamil and Ahmad, 2014, 2019). Due to non-technical losses, utilities lose electricity worth billions of dollars on an annual basis and to avoid such losses, the honest paying utility customers incur high tariffs and/or experience power outages (Jamil and Ahmad, 2019; Smith, 2004; Wesonga, 2020).

In 2016, only Uganda and Seychelles had financially sustainable utilities in SSA region. These utilities were able to cover their operating and maintenance costs to replace the existing assets rather than the future assets (Mukisa et al., 2021; Lawaetz, 2021; Trimble et al., 2016). A reduction in a country's electricity loss level enhances its electricity security. The lower the electricity losses are, the greater the financial sustainability of utilities, and thus, the electricity security index. This is because any additional revenue generation enhances utility cost recovery, fosters sector capitalization, and increases the sector's capacity to invest (Jiménez et al., 2014).

In the years 2020 and 2021, Uganda witnessed an increase in the theft of power and vandalism of electricity installations. Out of the 17.5% registered power losses, electricity theft accounts for 8.3% in Uganda (Wesonga, 2020). Such non-technical losses are attributed to factors like a less restraining law in place, lack of enforcement, and the criminals knowing they could get away with the crime (UMEME, 2022a). Vandals stole over 133 km of cable in just 12 months of 2021, causing unprecedented disruption of electricity supply in Western Uganda. As of 2022, electricity theft in Western Uganda stands at 72% followed by Eastern and Northern Uganda. Overall, the energy sector lost over UgX 26 billion[1] in stolen copper wires, vandalised transformers and poles amongst others in 2021 (UMEME, 2022b). Electricity affordability remains a key concern for many Ugandans. The government is urged to regulate the power tariffs such that all Ugandans can access power. Majority of people, particularly in the rural areas cannot afford to pay for electricity. Likewise, the initial connection fee to the power grid of UgX 720,883 is quite high for most people to afford. Such concerns are some of the key factors fostering the illegal power connections in the country (UMEME, 2021a). One of the power sector's priorities for 2022 is improving the operational efficiency through reducing energy losses to 14% from current 17.5% and achieving a revenue collection rate of 99.8% (UMEME, 2021b).

[1] Conversion rate UD$ 1 ≡ UgX 3597.

Several utilities in SSA countries offer subsidized connections and tariffs for electricity to their different customer groups. Uganda still offers the smallest block limited to the first 15 kWh per month consumed by a domestic customer (household) (Gaul et al., 2019; UMEME, 2020). Electricity use by households reduced in Uganda from 22.1% in 2016–2017 period to 18.9% IEA, 2019–2020 period (UBOS, 2021). For the periods 2016–2017 and 2019–2020, the grid electricity usage statistics for urban and rural areas' households reduced from 57.2% to 51% and 8.3%–5.2% while the solar photovoltaic usage statistics doubled (UBOS, 2021). IEA, 2019, only about 49% of Ugandans live in areas served by an electricity grid (Kakumba, 2021). Only one in any four Ugandans lives in a legally connected household to the national power grid. Rural dwellers and urban poor are least likely to be connected to the national grid (Kakumba, 2021). The initial connection, tariffs and monthly standard service fee for electricity being too expensive have been cited by households as some of the hindrances to grid electricity (UBOS, 2021).

Electricity consumption by households has been dropping over the years in Uganda. The electricity consumption of Tier 1–5 household customers was averagely 44 kWh per month, while the median electricity consumption was 26 kWh per month in 2017. The average household electricity consumption reduced to an average of 36 kWh per month in 2018 (Gaul et al., 2019). Investigations further revealed that about 63% of household customers consume less than one kWh per day or 30 kWh per month (Gaul et al., 2019).

At the national level, Uganda's poverty incidence decreased from 33.3% in 2009–2010 to 20.3% IEA, 2019–2020 (UBOS, 2021). The high poverty prevalence is also reflected in the low nominal monthly household income that was about UgX 416,000 in 2016–2017 period. The average monthly income in urban areas of UgX 703,000 was more than double the average monthly income of UgX 303,000 in rural areas in 2016–2017 period (UBOS, 2018). Such low household income raises the concern of electricity affordability and how much such households can spend on electricity monthly (Africa Progress Panel, 2015; Mukisa et al., 2021). Poor households spend much of their income on energy expenditures than the wealthy households, regardless of the fact that wealthy households consume more energy (Bacon et al., 2010a; Morrissey, 2017). Empirical investigations have revealed that poor households' energy expenditure is in the range of 5–20% of their income, with an average of 10% (Africa Progress Panel, 2015; Morrissey, 2017).

Notably, Uganda's electricity generation is mainly from renewable energy sources. Of the installed generation capacity of 1346.4 MW in 2021, renewable energy accounted for 92.5% and thermal based generation accounted for 7.5% (ERA, 2022). The renewable energy contribution comprises of 1072.9 MW for hydropower, 60.9 MW for solar photovoltaic (PV), and 111.7 MW for cogeneration/bagasse (ERA, 2022). Uganda has witnessed a growing demand for solar power home systems especially in rural areas, with estimated sales of about 10,000 solar home systems annually throughout the country, tapping into the abundant solar PV resource particularly in areas without grid access (Mukisa et al., 2022/04; MEMD, 2015). Even though Uganda highly relies on renewable energy sources, the challenge of electricity unaffordability remains a hindrance to national electrification. Sustainable Energy for All (SE4All) initiative set an action agenda of achieving 100% access to electricity in 2030, where 33% and 67% of the population would access electricity through off-grid and on-grid, respectively (MEMD, 2015). To achieve the SE4All action agenda of 100% access to electricity by 2030, the concern of electricity affordability must be addressed to guarantee national electricity security.

In Uganda, occurrences of electricity theft exist (Wabukala et al., 2022) amidst regulatory and technological measures in place to prevent and or alleviate this practice. At the same time, households continuously cite unaffordability among the factors for the slow transition from reliance on unclean biomass to electricity for their energy needs. However, the linkage between electricity theft, affordability, and electricity security is empirically unknown or untested. Critically, the country continues to experience electricity thefts while electricity uptake among households remains below national target of 100% (Uganda Vision, 2040). The policy challenge then is to develop a strategy that to can potentially discourage electricity theft while simultaneously making electricity affordable. In this context, the central question is: What policy option(s) can simultaneously reduce electricity theft while promoting affordability and electricity security in Uganda? This paper concentrates on this question for two reasons: First, there is lean literature on electricity theft and electricity security. Existing studies either concentrate on the drivers of electricity theft (Smith, 2004; Yakubu et al., 2018; Razavi and Fleury, 2019; Jamil, 2018; Saini, 2017; Depuru et al., 2011) or dominantly articulate measurement controversies regarding electricity security (Wabukala et al., 2022; Neelawela et al., 2019b; Sarhan et al., 2021; Larsen et al., 2017) without providing the associated impacts between the two constructs. Second, while deterrence and punitive measures (technological and legal) exist and have adequately been profiled in literature (Jamil and Ahmad, 2019; Smith, 2004; Sharma et al., 2016; Shokoya and Raji, 2019; Dike et al., 2015; Saini, 2017; Depuru et al., 2011) their implementation has not yielded expected targets. Given that electricity theft has a socio-economic dimension, a strategy that targets on reducing electricity theft while providing affordable alternatives for households may improve electricity security in Uganda. Therefore, this study makes the following contributions to the field of knowledge.

- Proposes a probabilistic method for predicting category composition of electricity users in a sample.
- Examines the utility revenue collected and lost to households.
- Assesses electricity affordability by households based on their income.
- Proposes alternative electricity billing schemes for household customers in Uganda.

The rest of this paper is arranged as follows. Section 2 discusses the literature review of the paper. Section 3 discusses the methodology used, while Section 4 gives the results and discussions of this study's findings. Finally, Section 5 gives the conclusions and policy implications of the paper, while the limitation of the study and the suggested future works are presented.

2. Literature review

Derived from the lessons of energy supply disruptions in the early 1970s of the famous "Arab oil embargo", electricity security is the capability of an electricity system to ensure uninterrupted availability of electricity by withstanding and recovering from disturbances and contingencies (IEA, 2021). This definition summarises three properties: operational security, adequacy, and resilience. However, though evolving, literature (Sarhan et al., 2021; Neelawela et al., 2019b; Larsen et al., 2017) has extended this definition to availability, accessibility, affordability, and sustainability of an electricity system. Compelling evidence shows that electricity stimulates economic growth (Neelawela et al., 2019a; Stern et al., 2019; Ateba and Prinsloo, 2018), creates jobs (Tourkolias et al., 2009), propels industrialisation (IEA, 2019; Ikpe and Torriti, 2018), and is a strong driver of socio-economic development (Neelawela et al., 2019a; Sovacool and Vera, 2014). This implies that expanding electrification could increase productivity and improve the quality of social services in an economy. Assessing electricity security involves internalizing the manifestations and factors that constitute or define it, including affordability dimensions.

Electricity theft constitutes a fundamental social threat to electricity security. Thus, securitizing electricity is paramount for socio-economic transformation. Justification is that theft could disrupt electricity supply, derail financial inflows of electricity producers, and negatively affect the overall development of the energy sector (Yakubu et al., 2018; Lewis, 2015). More specifically, the losses resulting from electricity theft could impede utilities from reducing revenue payable by customers, government failure to subsidize electricity consumption of socially sensitive users, and/or curtail the extension of electricity to the unserved poor and socially unprotected population (Yakubu et al., 2018; Lewis, 2015). Assessed at either country or community level, the causes of electricity theft, though ungeneralised, are a combination of socio-economic and behaviour factors (Never, 2015; Yakubu et al., 2018; Razavi and Fleury, 2019; Jamil, 2018). However, attention has largely been directed at efforts that combat or alleviate electricity thefts. Important to note, majority of theft-combat interventions continue to emphasize technology (Sharma et al., 2016; Shokoya and Raji, 2019; Dike et al., 2015) and downplay psycho-social factors (Jamil and Ahmad, 2019; Yakubu et al., 2018; Razavi and Fleury, 2019).

Threats to electricity security in Uganda have a natural, economic, environmental, and social profiling, notably, transmission and distribution losses. Transmission and Distribution losses take two forms; technical and non-technical losses (Saini, 2017). Technical Losses are the inevitable losses due to energy decadence during electricity transmission for long distances, borne to the power systems but can be reduced to optimal levels. Non-Technical Losses also defined as commercial losses, characterise losses in the distribution of electricity emerging from theft and other indiscretions by both customers and employees of electricity companies (Saini, 2017). Electricity theft could be executed through bypassing the electricity meter, tampering with the meter, illegally tapping electricity from the overhead feeder lines, and connivance of utility employees (Lewis, 2015; Saini, 2017).

Hooking unauthorized wires to electricity distribution cables, and irregular billing due to connivance between customers and utility employees are the prime tactics of electricity theft in Uganda. These occurrences, combined, have adversely affected the functionality of the electricity generation infrastructure, prompting widespread power blackouts and supply disruptions in Uganda. Specifically, in the first half of 2018 alone, UMEME Uganda Ltd, the country's monopoly electricity distributor, lost at least 40 transformers and other electricity supply infrastructure to vandalism and illegal connections, translating into an estimated annual average loss of 100 billion Ugandan Shillings (Independent, 2019). This behaviour continues to underscore Uganda's efforts towards the short- and long-term goals of increasing access to clean and sustainable energy to the population.

Electricity theft ratios in developed and developing countries differ substantially. For example, the theft rate in the US and the West Europe is reported as 1–2% (Yurtseven, 2015/12). In developing countries, on the other hand, such as India, Malaysia, Bangladesh and Turkey, the size of the loss is high. Existing data reveal India loses over 25% of their generated power, Brazil faces about 16% loss while China and US reportedly lose 6% and 5%, respectively (Yurtseven, 2015/12; Otuoze et al., 2020/08). As reported by (Otuoze et al., 2020/08), over 50% of anticipated revenue is loss to electricity thefts in most developing countries and in terms of actual revenue. Likewise, United States, India and Malaysia reportedly incur annual loss of about \$6 billion, \$16.2 billion and RM500 million, respectively as result of electricity theft (Sharma et al., 2016; Otuoze et al., 2020/08; Jiang et al., 2014). In Turkey, the Turkish Electricity Distribution Company ed that annually, about 16 billion kWh of electricity as stolen, which represents about 15% of the total supply of electricity, translating to billions of dollars in financial loss (Yurtseven, 2015/12). In Uganda, electricity theft is at about 8.3% (Wesonga, 2020).

Ref (Smith, 2004) investigated the causes of electricity theft and asserted that countries with ineffective accountability, unstable political environment, ineffective government, and corruption experience higher levels of electricity theft. By examining Pakistan, Ref (Jamil and Ahmad, 2014). that consumers' income and electricity price are key factors that influence electricity theft, noting that as consumers' income rises electricity theft reduces. Ref (Mirza and Hashmi, 2015). discussed the long run determinants of electricity theft for the case of Pakistan. It was found that in Pakistan, maximum population belongs to lower income groups which makes it is quite difficult for them to afford the electricity at such high rates that increase as time passes. Qualitatively, the impact of socio-economic factors on electricity theft in Uganda was assessed in 2014 (Never, 2015). It was deduced that high electricity price, absence of trust, informal social norm like bribery, and insufficient billing information drive medium and small enterprises (MSEs) to engage in power theft. Thus, existence of trust, explicit billing information, and availability of sub-meters are strong pre-conditions for efficient bulk metering for MSEs (Never, 2015).

In Ghana, grounded theory of qualitative research approach was used to understand the principal motivations of electricity theft (Yakubu et al., 2018). The study concluded that higher electricity prices, poor quality of power supplied, corruption, poor enforcement of the law against electricity theft were the prime causes of electricity theft. Crucially, a reduction in tariff and improvement in the quality of electricity supplied would propel more consumers to pay the right bills, and subsequently, contribute to electricity security (Yakubu et al., 2018). In Pakistan a qualitative design to investigate the central factors that contribute to electricity thefts among residential consumers in Pakistan was used (Jamil, 2018). Sampled consumers reported that electricity price hike was the principal driver of electricity theft. Crucially, monitoring, conduct (behaviour), and monthly expenses had a strong bearing on electricity theft (Jamil, 2018). In India, machine-learning models were deployed to quantify the predictive power of socio-economic variables in explaining the electricity theft (Razavi and Fleury, 2019). Study results showed that 87% of the variability of loss rate are associated with crime rate, literacy rate, income, urbanization, and the average electricity consumption per capita (Razavi and Fleury, 2019).

To address electricity theft, the vice was profiled in Nigeria and Smart Grid-Smart Metering was proposed to alleviate electricity theft (Shokoya and Raji, 2019). A smart Grid offered improved flexibility, security (theft detection) and reliability, and allows the integration of renewable energy sources into the conventional power grid which enhances electricity security (Shokoya and Raji, 2019). In another study, an algorithmic simulation that integrates grid smart metering (GSM) into prepaid energy meters to detect and report illegal loads on the electricity utility system was used (Dike et al., 2015). The GSM integration would provide real time detection when an illegal load is connected, and immediately alert the electricity company, regardless of the magnitude of the illegal load (Dike et al., 2015). Panel data analysis was considered to estimate the influence of socio-economic and governance factors on electricity thefts in India (Gaur and Gupta, 2016). Feasible generalized least squares (FGLS) estimation demonstrated that lower corruption prevalence, higher state tax-to-GDP ratio, increase in private installed capacity, lower poverty levels, and higher household income translate into lower electricity thefts (Gaur and Gupta, 2016).

Electricity theft is a form of corruption, where corruption is considered as any kind of fraudulent use of electricity wherein consumer and utility employee collude for their respective gains causing loss to the utility (Jamil and Ahmad, 2019). The individual considers the monetary value of unpaid electricity as benefits. By ignoring the diminishing marginal utility, the consumer's benefits equals stolen/un-reported units of electricity (Jamil and Ahmad, 2019). Study (Sharma et al., 2016) integrated 6 theories: person based; planned behaviour; differential association; fraud; crime; and organisational factors to examine psycho-social factors that propel employees to collude with consumers in electricity thefts. The investigation established that tapping of distribution lines, unauthorized electricity supply, resistance to pay, non-billing and under-billing, bypassing meters, and billing consumers at low rates are prime modes of electricity thefts. Also, the integrated framework was reported to contribute to grounded theory building on the factors that induce employees to connive with consumers in electricity theft (Sharma et al., 2016). A Case study approach to assess the factors that induce consumers to steal electricity, and effects of electricity theft on quality of supply, generation ability and impacts on genuine consumers were considered in (Depuru et al., 2011). It was concluded that dishonesty, unemployment, low literacy, poverty, weak law enforcements, corruption, high electricity prices, and lack of electricity supply in neighbourhoods propel consumers to steal electricity (Depuru et al., 2011).

Contrarily, Ref (Yurtseven, 2015/12). claims that the high rate of electricity theft in developing economies leads one to believe that poverty is the cause; however, in China the electricity theft rate is lower even though the poverty rate is high. Although (Yurtseven, 2015/12) believes that other factors such as social capital, population rate in rural areas, temperature rate, and production of agriculture cause electricity theft, the study never denied the influence that high rates has on electricity theft. Another study alluded to the fact that consumers may be dissuaded from purchasing electricity when prices are so high, even literate and higher income earners may also be motivated to avoid paying higher electricity bills (Depuru et al., 2011). Ref (Mutebi et al., 2014). alluded to the fact that economic reasons and fraud within the utility companies were the main motivating factors that encouraged consumers to electricity theft in Kampala, Uganda.

Due to escalading cases of electricity theft that hinder a sustainable electricity supply chain, several studies such as (Never, 2015; Mutebi et al., 2014; Depuru et al., 2011; Ahmad, 2017/05) advocate for the implementation of smart technologies to ward off energy thieves, and/or impose appropriate fines once theft occurs (Otuoze et al., 2020/08). But the fact that electricity theft continues to show upward trends amid these smart technology measures implies that technological fixes alone are not enough to curb the menace. The limitation of intelligent technology systems in completely resolving electricity theft, despite some marked successes, has been duly recognised by various researchers (Sharma et al., 2016; Sreenivasan, 2016). Beyond technological solutions, social interventions have been advocated for such as whistleblowing (Adongo et al., 2021/08; Arkorful, 2022). Although electricity theft crime resolution has socio-economic, psychological, ethical and technical underpinnings, the latter is mostly sought (Adongo et al., 2021/08). Little or no economic intervention has been investigated to address the continued electricity theft vice in developing countries. This focuses on the economic bottlenecks for electricity security in developing countries by using Uganda as the case study.

Becker's theory of the economics of criminal behaviour is considered one of the seminal ideas to consider in discussing issues of crime relating to economics. The theory stipulates that offenders are utility maximising agents who weigh subjective benefits and costs of offences so that offences are committed when the gains are more than cost. The theory also fits the homo economicus viewpoint which shows that economic agents (both offenders and crime gatekeepers) are not only utility maximising agents as consumers and optimisers of profits as producers but are also self-interested individuals who weigh personal gains and costs in their engagement with everyday economic goods or decisions (Jamil and Ahmad, 2019; Adongo et al., 2021/08). The consumers take advantage of the deficiencies in regulatory regimes and poor governance to avoid electricity charges. Sometimes electricity theft occurs without connivance of the utility employees while in most of the instances, utility employees facilitate electricity theft signifying the role of corruption (Jamil and Ahmad, 2014, 2019; Sharma et al., 2016).

The theory argues that the observed number of crimes in a society depends on relative return on legal and illegal activities, penalty for committing crime and the probability of being detected. The crime is committed only if the gain from offence exceeds the expected cost of crime (Jamil and Ahmad, 2019). The fines or sanctions imposed on offender depend on the social loss to the society due to the offence (Jamil and Ahmad, 2019). To curb electricity theft and vandalism in the country, the government of Uganda proposed fines of up to UgX 400 million, sentence of 10 years imprisonment, or both for power theft in an amendment in the Electricity Bill 2022. This is an adjustment to the current fine of UgX 600,000, sentence of 3 years imprisonment, or both for power theft (UMEME, 2022a). The Electricity Bill amendment also proposes a fine of up to UgX 1 billion for vandalizing electricity infrastructure or imprisonment for 13 years or both (UMEME, 2022a). This study labours to establish electricity affordability of electricity and economic factors for electricity theft. It is worth noting that households are likely never to afford the proposed fines for electricity theft if currently they cannot afford to pay for their electricity consumption bills based on their income.

For electricity theft, when consumers and sector employees are convinced beyond a reasonable doubt that pirating will inure to their advantage at minimal or no cost, they will be motivated to undertake certain investments to engage in it (Jamil and Ahmad, 2019). The study concluded that, first, individuals steal electricity if associated gains outweigh associated costs. Second, corruption spurs electricity theft. Finally, efficiency wages, higher deterrence, and whistleblowing by consumers abates corruption and reduces electricity thefts (Jamil and Ahmad, 2019).

The share of electricity loss due to illegal connections has been rising over the past years in Uganda. For instance, the percentage of electricity losses resulting from theft rose from 6.6% in 2018 to 8.3% IGC, 2020 (Wesonga, 2020). Households attribute electricity stealing to electricity high tariffs, delays in connecting to the grid of over a fortnight, high initial connection fee, and lack of incentive for those that snitch on electricity thieves (Wesonga, 2020). Illegal connections pose a great risk to the utility infrastructure as it causes system overload, which often results in electricity tripping off or failure and could cause a fire outbreak (Lewis, 2015; Reporter, 2019). Likewise, since illegal connected are not carefully integrated and wired, electrocution risks are very high (Reporter, 2019). Although high tariffs are one of the reasons given for electricity theft, existence of this vice directly influences an increase in the tariffs for the utilities to uphold their economic viability (Lewis, 2015).

Illegal connections lead to loss of lives due to electrocution, destruction of utility infrastructure equipment and economic losses to the other utility customers that are not engaged in the theft vice due to power supply outages (Lewis, 2015; UMEME Kampala, 2018). For instance, the 2018 incident report found that illegal electricity connections accounted for 48% of the electrocution cases in Uganda (Wesonga, 2020). Due to electricity theft, UMEME recorded an annual revenue loss of US$20 million in 2018 (UMEME Kampala, 2018). To address the electricity theft vice, UMEME implemented a customer outreach campaign in 2017 to sensitize the citizenry about the dangers of electricity theft and vandalism (UMEME Kampala, 2018). However, to date, no substantial results have been registered by the institution, given the current prevalence of the vice in the country.

Electricity theft has several socio-economic determinants which influence all the fore-mentioned forms, e.g., corruption, literacy, income, tariff rate, collection efficiency, risk factor, population, and many others. These socio-economic determinants for electricity theft in a society are shown in Fig. 1 (Saini, 2017). Notably, some of these socio-economic determinants impact electricity theft positively, like corruption, while others impact it negatively, like literacy and collection efficiency. These determinants showcase the attitude of people in a society towards electricity theft in different geographical areas (Saini, 2017).

IGC, 2020, about 30.1%, an equivalent of 12.3 million of Ugandans living in poverty spent less or $ 1.77 per person per day. Approximately 33.8% of the rural population and 19.8% of the urban population live in poverty in Uganda. Thus, 8.3 million Ugandans live on less or $ 1 per person per day, 12.3 million Ugandans live on less or $ 1.77 per person per day, while 16.9 million Ugandans live on less or $ 1.9 per person per day (UBOS, 2021). The median earning for an employee in Uganda was UGX 200,000 IGC, 2020, where employees in the urban area earned averagely UgX 300,000, which is more than double average earning of UgX 130,000 for employees in the rural areas (UBOS, 2021). The average distribution of household income by source in Uganda is 52.8%, 18.9%, 18.5%, and 9.8% from substance agriculture, commercial farming, wage employment, and others, respectively (UBOS, 2021).

Fig. 1. Socio-economic determinants of electricity theft.

Thus, it is evident that household income is mainly seasonal and dependent on agricultural yield and prices, which are volatile.

3. Methodology

Estimations of electricity consumption generally incorporate the price of electricity consumed as well as other charges (such as service charges and taxes) (Yurtseven, 2015/12; Maria de Fátima et al., 2012). In this study, the electricity consumption by households through official (legal) connection and illegal connection is modelled. Therefore, different sets of characteristics are used than the one that is used to estimate electricity demand. Furthermore, given the nature of data limitations for Uganda, this study adopted a probabilistic approach in undertaking the assessments (Etikan and Bala, 2017). Also, the available data on electricity access or connectivity is reported on a basis of a percentage of the population that has access to national grid.

In this study therefore, the probabilities that a household in rural areas is connected ($p(HH_{cg,r})$) and not connected ($p(HH_{ng,r})$) to the national power grid were estimated as 0.25 and 0.75, respectively. The probabilities that a household in urban areas is connected ($p(HH_{cg,u})$) and not-connected ($p(HH_{ng,u})$) to the national power grid were estimated as 0.5 and 0.5, respectively. This study also assumed a probability of electricity theft of 0.2 for connected urban household ($p(HH_{p,u})$) and 0.4 for not-connected urban household ($p(HH_{a,u})$), while it assumed a probability of electricity theft of 0.1 for connected rural household ($p(HH_{p,r})$) and 0.6 for not-connected rural household ($p(HH_{a,r})$).

A consumer faces the choice of whether or not to commit electricity theft. The decision depends on a number of random factors, some of which are assumed to be known to consumer before makes the decision. To quantify analysis, this study considered a total random sample size of 2000 households, where 1000 households are in rural areas (N_r) and 1000 households are in urban areas (N_u) covered by the national power grid (i.e., $N_u = N_r$). Thus, the assumed numbers for connected households that are genuinely metered N_g, connected households that partially steal electricity N_p, not-connected household but steal electricity N_a, and not-connected households that also don't steal electricity $N_{a'}$ are evaluated by using Eqs. (1)–(4) and Eqs. (5)–(8) for urban and rural households, respectively.

$$N_{g,u} = p\left(HH_{cg,u}\right) \bullet \left(1 - p\left(HH_{p,u}\right)\right) \bullet N_u \tag{1}$$

$$N_{p,u} = p\left(HH_{cg,u}\right) \bullet p\left(HH_{p,u}\right) \bullet N_u \tag{2}$$

$$N_{a,u} = p\left(HH_{ng,u}\right) \bullet p\left(HH_{a,u}\right) \bullet N_u \tag{3}$$

$$N_{a',u} = p\left(HH_{ng,u}\right) \bullet \left(1 - p\left(HH_{a,u}\right)\right) \bullet N_u \tag{4}$$

$$N_{g,r} = p\left(HH_{cg,r}\right) \bullet \left(1 - p\left(HH_{p,r}\right)\right) \bullet N_r \tag{5}$$

$$N_{p,r} = p\left(HH_{cg,r}\right) \bullet p\left(HH_{p,r}\right) \bullet N_r \tag{6}$$

$$N_{a,r} = p\left(HH_{ng,r}\right) \bullet p\left(HH_{a,r}\right) \bullet N_r \tag{7}$$

$$N_{a',r} = p\left(HH_{ng,r}\right) \bullet \left(1 - p\left(HH_{a,r}\right)\right) \bullet N_r \tag{8}$$

Considering that the average household electricity consumption was 36 kWh per month in 2018, with over about 63% of household customers consuming less than one kWh per day or 30 kWh per month (Gaul et al., 2019), it was assumed in this investigation that the average household electricity consumption is 30 kWh and 45 kWh per month for rural (C_r) and urban (C_u) areas in 2022, respectively. Thus, for genuine electricity households (customers), partial electricity stealing customers, and all-electricity stealing households, these average household electricity consumption units were considered for the case of urban and rural households in the analysis. It was assumed that partial electricity stealing households pay for only 60% of the household monthly electricity consumption. Thus, partial electricity stealing households in urban and rural areas are billed for 27 kWh and 18 kWh, respectively, every month.

The methodology is divided into three subsections. Subsection 3.1 presents the method for assessing household electricity theft and utility losses, Subsection 3.2 presents the affordability of electricity costs by households, and Subsection 3.3 presents the alternative electricity billing schemes for households.

3.1. Household electricity theft and utility losses

A household is assumed to consume C units (C_u for urban and C_r for rural) of electricity at a domestic tariff rate of α. For a genuine electricity household HH_g that is legally connected to the grid and is metered for all its electricity consumption, the household's actual expenditure on consumed electricity E_g as billed by the utility is evaluated by using Eqs. (9) and (10) for urban and rural customer, respectively.

$$E_{g,u} = \left[\left(\alpha_{15} \bullet C_{u,15}\right) + \left(\alpha_{15'} \bullet \left(C_u - C_{u,15}\right)\right)\right] \bullet \left(1 + V_c\right) + M_s \tag{9}$$

$$E_{g,r} = \left[\left(\alpha_{15} \bullet C_{r,15}\right) + \left(\alpha_{15'} \bullet \left(C_r - C_{r,15}\right)\right)\right] \bullet \left(1 + V_c\right) + M_s \tag{10}$$

where, V_c is the value added tax rate on the consumed electricity units in a billing period (a month), and M_s is the monthly standard service fee. α_{15} and $\alpha_{15'}$ are the electricity tariff for the first 15 kWh (subsidized lifeline units) and above 15 kWh (unsubsidized units) of electricity consumed by a household. $C_{u,15}$ and $C_{r,15}$ are the first 15 kWh of electricity consumed by a household in urban and rural areas, respectively. $C_{u,15'}$ (i.e., ($C_u - C_{u,15}$)) and $C_{r,15'}$ (i.e., ($C_r - C_{r,15}$)) are the above 15 kWh of electricity consumed by a household in urban and rural areas, respectively.

An electricity stealing household could be described as a partial or an all-electricity stealing. A partial electricity stealing household HH_p is one that is legally connected to the electricity grid but interferes with the electricity meter and conceals some units of the consumed electricity. Thus, a partial electricity stealing household only pays for X units (X_u for urban and X_r for rural) and the concealed electricity units T_p ($T_{p,u}$ for urban and $T_{p,r}$ for rural), given by Eqs. (11) and (12) for urban and rural customer, respectively. An all-electricity stealing household HH_a is one that is illegally connected to the electricity grid and thus has no official billing records with the electricity distributing company. The electricity units consumed by an all-electricity stealing household T_a ($T_{a,u}$ for urban and $T_{a,r}$ for rural) are given by Eqs. (13) and (14)) for urban and rural customer, respectively.

$$T_{p,u} = C_u - X_u \tag{11}$$

$$T_{p,r} = C_r - X_r \tag{12}$$

$$T_{a,u} = C_u \tag{13}$$

$$T_{a,r} = C_r \tag{14}$$

For the two categories of electricity stealing households, the utility bill for the partial electricity theft E_p ($E_{p,u}$ for urban and $E_{p,r}$ for rural) is given by Eqs. (15) and (16) for urban and rural customer, respectively. The utility registers a pecuniary loss G_p ($G_{p,u}$ for urban and $G_{p,r}$ for rural) given by Eqs. (17) and (18) for urban and rural customer, respectively, to the partial electricity theft. The utility loss to all-electricity stealing household G_a ($G_{a,u}$ for urban and $G_{a,r}$ for rural) is given by Eqs. (19) and (20) for urban and rural households, respectively.

$$E_{p,u} = \left[\left(\alpha_{15} \bullet X_{u,15}\right) + \left(\alpha_{15'} \bullet \left(X_u - X_{u,15}\right)\right)\right] \bullet (1 + V_c) + M_s \tag{15}$$

$$E_{p,r} = \left[\left(\alpha_{15} \bullet X_{r,15}\right) + \left(\alpha_{15'} \bullet \left(X_r - X_{R,15}\right)\right)\right] \bullet (1 + V_c) + M_s \tag{16}$$

$$G_{p,u} = \alpha_{15'} \bullet T_{p,u} \bullet (1 + V_c) \tag{17}$$

$$G_{p,r} = \alpha_{15'} \bullet T_{p,r} \bullet (1 + V_c) \tag{18}$$

$$G_{a,u} = \left[\left(\alpha_{15} \bullet T_{a,u,15}\right) + \left(\alpha_{15'} \bullet \left(T_{a,u} - T_{a,u,15}\right)\right)\right] \bullet (1 + V_c) + M_s \tag{19}$$

$$G_{a,r} = \left[\left(\alpha_{15} \bullet T_{a,r,15}\right) + \left(\alpha_{15'} \bullet \left(T_{a,r} - T_{a,r,15}\right)\right)\right] \bullet (1 + V_c) + M_s \tag{20}$$

where, $X_{u,15}$, $X_{r,15}$, $T_{a,u,15}$ and $T_{a,r,15}$ represent the first 15 kWh of electricity consumed by a household.

The end-user tariffs for household electricity customers approved by the Electricity Regulatory Authority (ERA) for 2022 are shown in Table 1 (Gaul et al., 2019; UMEME, 2020; UMEME, 2022c).

Total utility revenue collection (R_g) from the legally connected and genuine customers in urban areas $R_{g,u}$ and rural areas $R_{g,r}$ is evaluated by using Eqs. (21) and (22), respectively. The utility revenue collection from the legally connected but partial electricity stealing customers in urban areas $R_{p,u}$ and rural areas $R_{p,r}$ is evaluated by using Eqs. (23) and (24), respectively.

$$R_{g,u} = E_{g,u} \bullet N_{g,u} \tag{21}$$

$$R_{g,r} = E_{g,r} \bullet N_{g,r} \tag{22}$$

$$R_{p,u} = E_{p,u} \bullet N_{p,u} \tag{23}$$

$$R_{p,r} = E_{p,r} \bullet N_{p,r} \tag{24}$$

Total utility revenue losses (L_p) to the legally connected but partial electricity stealing customers in urban areas $L_{p,u}$ and rural areas $L_{p,r}$ is evaluated by using Eqs. (25) and (26), respectively. Total utility revenue losses (L_a) to the illegally connected all-electricity stealing households in urban areas $L_{a,u}$ and rural areas $L_{a,r}$ is evaluated by using Eqs. (27) and (28), respectively.

$$L_{p,u} = G_{p,u} \bullet N_{p,u} \tag{25}$$

$$L_{p,r} = G_{p,r} \bullet N_{p,r} \tag{26}$$

$$L_{a,u} = G_{a,u} \bullet N_{a,u} \tag{27}$$

$$L_{a,r} = G_{a,r} \bullet N_{a,r} \tag{28}$$

Generally, the method described in this sub-section is replicable and can be applied anywhere. The variation could only be on whether the considered location offers a lifeline tariff or a flat tariff for domestic customers. If it does offer a lifeline tariff, the electricity units under the lifeline would be applied. Else, the equations with a lifeline variable would be modified to only represent a flat tariff.

3.2. Affordability of electricity costs by households

Since households are assumed to be near a pole and desire to be legally connected to the grid, such a household incurs inspection fees and wireless split meter. The initial connection fee C_i to power grid is given by Eq. (29).

$$C_i = I_f + C_f \tag{29}$$

where, I_f is the inspection fee and C_f is the connection fee (wireless split meter – no pole or bare conductor wireless meter – one pole). The standard charges for domestic customers, that is, residential houses, salons, kiosks and shops for new (initial) connection to the power grid are shown in Table 2 (UMEME, 2022d).

To establish electricity affordability of a household, it is important to know the household's income and other expenditures incurred over the specified period, that is, month or year. A monthly household income I_m (urban $I_{m,u}$ and rural $I_{m,r}$) is considered, where a share of the monthly household income $I_{e,u}$ for urban and $I_{e,u}$ for rural households is spent on electricity consumption. The estimate of the amount spent by a household on electricity is given by Eqs. (30) and (31) for urban ($SE_{m,u}$) and rural ($SE_{m,r}$) households, respectively.

$$SE_{m,u} = I_{e,u} \bullet I_{m,u} \tag{30}$$

$$SE_{m,r} = I_{e,r} \bullet I_{m,r} \tag{31}$$

To assess electricity affordability of a household, electricity units $A_{e,u}$ and $A_{e,r}$ that urban and rural households could procure using the available income dedicated to electricity (evaluated by using Eqs. (30) and (31)) are given by Eqs. (32) and (33), respectively.

$$A_{e,u} = \frac{\left(SE_{m,u} - M_s\right) - \left(\alpha_{15} \bullet C_{u,15}\right) \bullet (1 + V_c)}{(1 + V_c) \bullet \alpha_{15'}} + \alpha_{15} \tag{32}$$

$$A_{e,r} = \frac{\left(SE_{m,r} - M_s\right) - \left(\alpha_{15} \bullet C_{r,15}\right) \bullet (1 + V_c)}{(1 + V_c) \bullet \alpha_{15'}} + \alpha_{15} \tag{33}$$

The duration it would take for a household to pay the entire initial connection fee $t_{c,u}$ for urban area and $t_{c,r}$ for rural area is evaluated by using Eqs. (34) and (35), respectively.

$$t_{c,u} = \frac{C_i}{SE_{m,u}} \tag{34}$$

Table 1
End-user tariffs for household electricity customers 2022.

Customer category	Notation	Consumption range	Tariff (UgX/kWh)
Domestic or Household consumers	α	First 15 kWh in a month	250
		Units between 16 and 80 kWh	747.5
		Units between 81 and 150 kWh	412.0
		Units above 150 kWh	747.5
Monthly standard service fee	M_s	UgX 3360	
Value Added Tax (VAT) applicable	V_c	18%	

Table 2
New connection to electricity grid charges for households.

Entity	Cost (UgX)
Inspection fee	41,300
Wireless split meter – No pole	720,883
Bare conductor wireless meter – One pole	2,387,472

$$t_{c,r} = \frac{C_i}{SE_{m,r}} \tag{35}$$

The household income and how it is spent to meet their needs were considered to ascertain some of the reasons for electricity theft by the domestic customers. Table 3 shows the annual household income by grouping for Uganda (UBOS, 2021). Table 4 shows the breakdown of the monthly household expenditure by consumption purpose in Uganda (UBOS, 2021).

As shown in Table 4, household electricity expenditure is included under Housing, water, electricity, gas, and other fuels category other than as an independent consumption category. It is complex to exactly estimate the household expenditure on electricity alone. An investigation on household expenditure revealed that annually $ 78.81–94.43 is spent on only lighting and phone charging in Uganda (Mukisa et al., 2022/04). Study (Bacon et al., 2010b) reported that rural and urban households in Uganda spend 4.0% and 3.4% of their income on electricity alone, respectively. In addressing the electricity theft vice, it is important to consider the occupancy tenure of the dwelling units and their sizes. Table 5 shows the rural and urban households tenure of dwelling units and number of sleeping rooms as well as the average number of occupants per sleeping room in Uganda (UBOS, 2021).

The method described in this sub-section is replicable and generalizable. The variation could only be on whether the considered location offers a lifeline tariff or a flat tariff for domestic customers. If it does offer a lifeline tariff, the electricity units under the lifeline would be applied. Else, the equations with a lifeline variable would be modified to only represent a flat tariff. Also, it is important acquire data of the share of household income spent on energy services and initial connection to grid network cost on the considered location.

3.3. Alternative household electricity billing schemes

Research has revealed that several households complain of the current electricity tariffs as unaffordable, arguing that these tariffs should be lowered (Never, 2015; Smith, 2004; Wesonga, 2020; Yakubu et al., 2018; Mirza and Hashmi, 2015; Jamil, 2018). To propose alternative household electricity billing schemes, four scenarios were investigated in this study. The considered scenarios are as follows.

Scenario A: maintain the current billing scheme along with the monthly standard service fee and value added tax

Scenario B: offer a flat tariff for all consumed electricity of less than 80 kWh of UgX 450 and UgX 750 for electricity consumption 80 kWh and above along with the monthly standard service fee and value added tax

Scenario C: maintain the current billing scheme along with the monthly standard service fee, but exempt households of value added tax

Scenario D: maintain the current billing scheme along with the value added tax, but exempt households of monthly standard service fee

Table 6 shows the breakdown of the considered household alternative electricity billing schemes in this study, Value Added Tax, and monthly standard service fee. These scenarios we used to assess the respective electricity bills that a household would incur in a month. Likewise, a sensitivity analysis was undertaken to assess the effect of varying the parameters of the considered scenarios on the monthly electricity bill incurred by the household.

Table 3
Annual household income by grouping for Uganda.

Household income category	Share of the population (%)
Less than 1 m	2.0
1m - less than 5m	12.6
5m - less than 10m	75.6
10m - less than 15m	4.0
15m - less than 20m	2.0
20m - less than 25m	0.9
25m and above	2.9

Table 4
Monthly household expenditure by consumption purpose in Uganda.

Consumption purpose	Share of total expenditure (%)
Food and non-alcoholic beverages	42.9
Alcohol beverages, tobacco, and spirits	0.9
Clothing and footwear	2.3
Housing, water, electricity, gas, and other fuels	17.4
Furnishing, household equipment	3.2
Health	5.6
Transport	8.9
Communication	3.5
Recreation and culture	1
Education	8.5
Restaurants and hotels	0.2
Insurance	0.2
Miscellaneous goods and service	2.2
Non-consumption expenditures	3.2

Table 5
Household occupancy tenure of dwelling unit and number of sleeping rooms for Uganda.

Households by occupancy tenure of dwelling unit		
Occupancy tenure	Rural (%)	Urban (%)
Owner Occupied	90.2	52
Rented	5.9	41
Free	3.8	7
Household by number of sleeping rooms and average occupants		
One Room	35.2	51
Two Rooms	31.2	25.5
More than two rooms	33.6	23.5
Average occupants per room	2.6	2.3

Table 6
Breakdown of scenarios for household electricity billing schemes.

Entity	Scenario A	Scenario B	Scenario C	Scenario D
Tariff rate for electricity consumed	• $\leq$ 15 kWh @ UgX 250 • 16–80 kWh @ UgX 747.5 • 81–150 kWh @ UgX 412.0 • $\geq$ 150 kWh @ UgX 747.5	• $\leq$ 40 kWh @ UgX 450 • 41–150 kWh @ UgX 747.5 • $\geq$ 150 kWh @ UgX 1000	• $\leq$ 15 kWh @ UgX 250 • 16–80 kWh @ UgX 747.5 • 81–150 kWh @ UgX 412.0 • $\geq$ 150 kWh @ UgX 747.5	• $\leq$ 15 kWh @ UgX 250 • 16–80 kWh @ UgX 747.5 • 81–150 kWh @ UgX 412.0 • $\geq$ 150 kWh @ UgX 747.5
Value Added Tax	18%	18%	0	18%
Monthly standard service fee	UgX 3360	UgX 3360	UgX 3360	0

4. Results and discussions

4.1. Household electricity theft and utility losses

By using the respective information in Eqs. (1)–(8), the number of households in each category was evaluated for both urban and rural areas covered by the national electricity grid. Table 7 shows the number of households in different categories as applied in this study.

Table 7 shows that three quarters of the considered sample of 1000

Table 7
Number of households in each category for urban and rural areas covered by the electricity grid.

Household category	Urban		Rural	
Genuine electricity household	$N_{g,u}$	400	$N_{g,r}$	225
Partial electricity stealing household	$N_{p,u}$	100	$N_{p,r}$	25
All-electricity stealing household	$N_{a,u}$	200	$N_{a,r}$	450
Non-electricity using household	$N_{a',u}$	300	$N_{a',r}$	300

rural households are not legal customers of the utility, that is, they are either illegally connected to the grid or are not using electricity at all. For the urban households, half of the sample is not legally connected to the grid. The values for the different household categories in Table 7 are influenced by the probabilities used in this analysis to mimic the real-life situation in Uganda. It should be noted that for different rural and urban communities, the pattern for legal and illegal connections to electricity and without electricity varies and it is quite hard to generalize or predict the one-fits-all figures to consider.

To determine the electricity expenditure of each household based on its category, Eqs. (9), (10) and (15) – (20) were used to evaluate the utility revenue collected and losses incurred. Table 8 shows the monthly utility revenue collected and concealed (loss) by the utility for the electricity consumption by household categories both in urban and rural areas covered by the national electricity grid.

Table 8 reveals that the utility would collect revenue of about 53.64% and 49.63% of all the electricity consumed by a partial electricity household in the urban and rural areas, respectively. Although partial electricity stealing households in both rural and urban areas pay for 60% of the consumed electricity, the 18 kWh that the rural household pays for mainly constitutes of the first 15 kWh that are sold at UgX 250 and only 3 kWh that are sold at UgX 747.5, whose billing results in a value lower than that of the concealed 12 kWh that are all evaluated at a rate of UgX 747.5. Likewise, the 27 kWh that urban partial electricity stealing household pays for constitutes of the first 15 kWh that are sold at UgX 250 and 12 kWh that are sold at UgX 747.5, whose billing results in a value higher than that of the concealed 18 kWh that are sold at UgX 747.5. Thus, it could be asserted that for the partial electricity stealing household, the lower the electricity consumption in a billing period is, the higher the revenue loss the utility incurs is and vice versa.

The data in Tables 7 and 8 were applied to Eqs. (21) – (24) and (25) – (28)to evaluate the total utility revenue collected and lost, respectively, for the different household categories. Fig. 2 a) shows the utility revenue collected, while Fig. 2 b) shows the utility revenue lost from the sample size of households considered in this study.

Fig. 2 a) shows that the total utility revenue collected from the genuine customers in the urban area is more than 2.9 times that of rural areas. This is attributed to the high number of genuine customers in urban areas (in Table 7) as well as the fact that every urban customer consumes 1.5 times the electricity consumed by the rural customer, hence the very high revenue collected from the urban area. Fig. 2 b) reveals that the utility incurs more revenue losses to rural all-electricity stealing households than in the urban area because of the higher of all-electricity stealing households in the rural area than in the urban area as shown in Table 7. The reason for the high all-electricity stealing households in the rural areas could be attributed to the low surveillance by the utility teams in rural areas compared to the urban areas. Thus, this result demonstrates that the utility needs to intensify surveillance and monitoring interventions of the electricity meters and grid to curb such high revenue losses to electricity theft.

4.1.1. Sensitivity analysis of utility revenue collected and lost

A sensitivity analysis of the utility revenue collected to the variation in the probabilities of the sample and billing parameters was undertaken by considering a variation in the range $\pm 50\%$ of any of the assessment entities while keeping the rest constant. Fig. 3 shows the sensitivity of the total utility revenue collected to the variation in the probabilities and billing parameters.

Fig. 3 a) shows that the total utility revenue collected over the study samples, both rural and urban, is highly sensitivity to the variation in the total electricity consumed by rural households, urban households, and partial electricity paid for by the urban households, while it has a slight sensitivity to the other considered parameters. The total utility revenue collected increases with the increase in the urban electricity consumption per household, while it reduces with the increase in the rural electricity consumption per household. This is because rural areas have a high number of all-electricity stealing households as shown in Table 7. Thus, as the electricity consumption increases for rural households, the increase in the utility losses to the electricity stealing households outweighs the increase in the utility revenue collected. On the other hand, since urban areas have a low number of all-electricity stealing households as shown in Table 7, thus, as the electricity consumption increases for urban households, the increase in utility revenue collected from genuine and partial electricity stealing households outweighs the utility losses to the electricity stealing households. Also, an increase in the share of the electricity paid for by the partial electricity stealing household increases the utility revenue collected. This is mainly because urban areas have a high number of partial electricity stealing households compared to the rural area. Likewise, urban households have a higher electricity consumption than the rural households.

Fig. 3 b) shows that the utility revenue collected is highly sensitive to the probability of the urban households that are legally connected to the grid $p(HH_{cg,u})$, followed by probability of the rural households that are not-connected to the grid $p(HH_{ng,r})$ and the probability of all-electricity stealing households in the rural area $p(HH_{a,r})$. An increase in the probability of urban households that are legally connected to the grid $p(HH_{cg,u})$ results is a significant increase in the utility revenue collected, while an increase in both the probability of the rural households that are not-connected to the grid $p(HH_{ng,r})$ and the probability of all-electricity stealing households in the rural area $p(HH_{a,r})$ results in a decrease in the utility revenue collected. Overall, from Fig. 3 b), it is evident that the utility revenue collected is sensitive to all the considered probabilities with a varying magnitude.

4.2. Affordability of electricity costs by households

Table 7 revealed that from the considered households sample size, there are 500 households in the urban area and 750 households in the rural area that are not legally connected to the grid. Of these households,

Table 8
Monthly utility revenue collected and concealed by the household categories.

Household category	Urban				Rural			
	Paid		Concealed		Paid		Concealed	
	UgX	%	UgX	%	UgX	%	UgX	%
Genuine electricity household	34,246.5	100	0	0	21,015.75	100	0	0
Partial electricity stealing household	18,369.6	53.64	15,876.9	46.46	10,431.15	49.63	10,584.6	50.37
All-electricity stealing household	0	0	34,246.5	100	0	0	21,015.75	100
Non-electricity using household	0	0	0	0	0	0	0	0

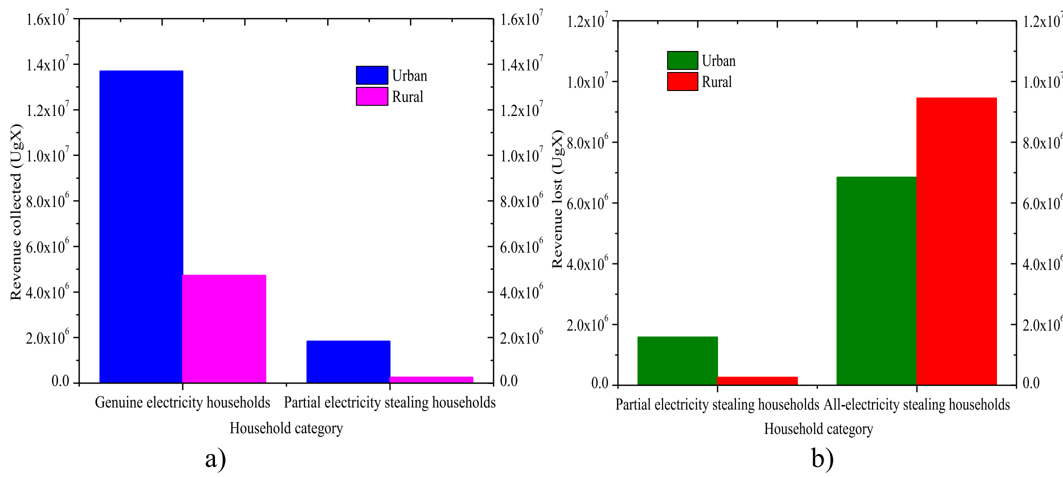

Fig. 2. a) Total utility revenue collected; b) Total utility revenue lost for the considered household sample size.

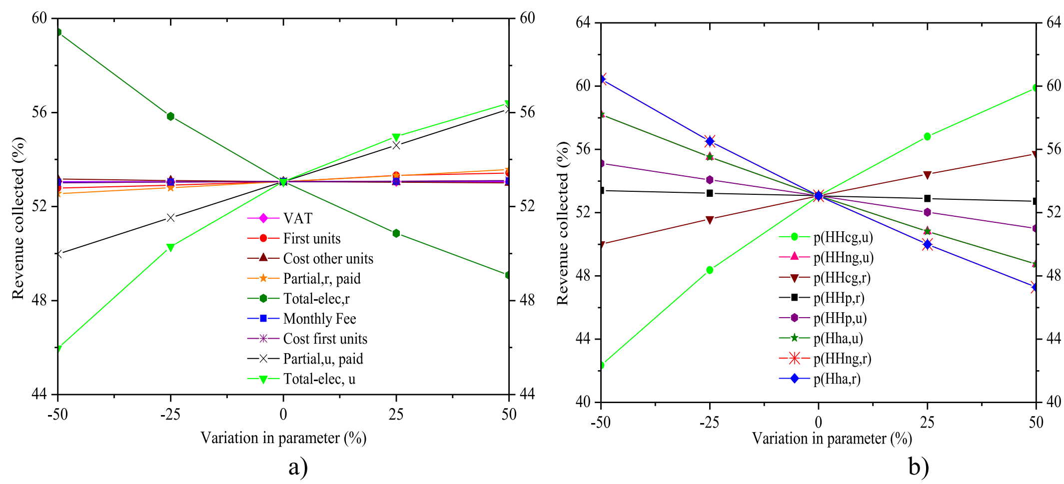

Fig. 3. Sensitivity of total utility revenue collected to variation in: a) Probabilities; b) Billing parameters.

200 in urban and 450 in rural areas are illegally connected to the grid and are consuming electricity without being billed, while 300 in urban and 300 in rural areas are not using any electricity from the power grid. Thus, the utility could expand its customer base by devising strategies for having these households convinced to get connected to the power grid legally. One of the ways of convincing this target group of potential utility customers is by assessing their ability to afford the initial connection fee as well as average monthly electricity consumption bills.

The inspection and wireless split meter-no pole data in Table 2 was used in Eq. (29) to determine the household's total initial connection fee. It was determined that a household would have to incur a total initial connection fee of UgX 762,183 to be legally connected to the power grid by the utility. To ascertain the household's affordability of the initial connection fee as well as its possible monthly electricity costs, the household monthly income was considered.

IGC, 2020, it was estimated that averagely an employee earned UgX 300,000 in urban areas and UgX 130,000 in rural areas (UBOS, 2021). Also, as indicated in Table 5, on average more than one person occupy any given dwelling in Uganda. Thus, based on Table 3, it was assumed that households in rural areas have an annual income in the range of UgX 1–5 million, while households in urban areas have an annual income in the range of UgX 5–10 million. In this assessment, the upper boundary of the annual income range for households was used to determine the monthly household income shown in Table 9. Also, Table 9 shows the share of the monthly household income dedicated to

Table 9
Affordable electricity units by households in urban and rural areas in Uganda.

Entity	Notation	Urban	Rural
Average monthly income (UgX)	I_m	833,333.3	416,666.7
Share of average monthly income spendable on electricity (%)	I_e	3.4	4
Monthly income spendable on electricity (UgX)	SE_m	28,333.33	16,666.67
Procurable electricity units (kWh)	A_e	38.29	25.07
Duration to clear the initial connection cost (months)	t_c	26.90	45.73

electricity evaluated by using Eqs. (30) and (31). Likewise, Table 9 shows the amount of electricity units that a household could afford to procure, evaluated by using Eqs. (32) and (33). A share of average monthly income dedicated to electricity in study (Bacon et al., 2010b) of 4.0% and 3.4% for rural and urban households, respectively, was used in Eqs. (30) and (31). Table 9 also shows the duration it would take a household to pay the initial connection fee of UgX 762,183 based on its monthly income spendable on electricity.

From the average monthly income in Table 9, a household in the rural and urban areas might not be able to pay in a single down payment the entire initial connection fee of UgX 762,183 to be legally connected to the grid. Based on the monthly income spendable on electricity in Table 9, it would take several months, about 26.90 months for an urban household and 45.73 months for a rural household to save the required initial connection fee to legally be connected to the power grid. This duration is a key indicator of why several households in national power grid covered areas opt to illegally connect to the grid because they cannot afford the initial connection fee in a single down payment. In November 2018, Uganda government adopted the electricity connection policy to offer free electricity connection to households. The scheme saw over 240,000 households connected to the grid annually for the years 2019 and 2020. However, the scheme was suspended in December 2020 because the government had failed to secure funds to pay the service providers (Ojok, 2021). UMEME reports indicate that it currently receives over 1000 applications daily for free electricity connection from household, but unfortunately they have not yet received funds from the government to resume connecting households under the scheme (Ojok, 2021). Thus, with the suspension of the electricity connection policy, households should probably be permitted to pay their initial connection fee in instalments over a specified period of months.

Table 9 reveals that households can only afford to procure 38.29 kWh and 25.07 kWh per month in urban and rural areas, respectively. This is mainly attributed to the monthly income and the income dedicated to electricity expenses. From the 45 kWh and 30 kWh for urban and rural areas, respectively, that were assumed as the monthly electricity consumption of households in Uganda, it is evident that most of the households might not be in position to afford to pay the monthly electricity bills if their share of monthly income spendable on electricity in Table 9 is considered. Therefore, for such household to faithfully pay for their monthly electricity bills, they might have to increase their share of monthly income spendable on electricity or reduce their monthly electricity consumption. This assertion is consistent with the reported fact that about 63% households consume less than 1 kWh daily in Uganda (Gaul et al., 2019). The challenge of electricity affordability remains a major hindrance to electricity consumption per capita. Uganda's envisioned annual electricity consumption of 578 kWh per capital by 2025 (NPA, 2020; IGC, 2020) remains far-fetched based on the household income and share of income dedicated to electricity expenses. For the households to enhance their electricity consumption, there is necessity for revising the country's electricity billing scheme.

4.2.1. Sensitivity analysis of household electricity affordability

It is quite complex to exactly estimate the average monthly income of households given the wide disparity between the poor and non-poor. For instance, over 16.9 million Ugandans live on less or $ 1.9 per person per day (UBOS, 2021). Thus, to have a better representation of monthly income of households and their affordability of electricity, a sensitivity analysis was undertaken. The household's procurable electricity units were assessed for sensitivity to the variation in input parameters in the range ±50%. Fig. 4 shows the sensitivity of the monthly procurable electricity units of a household to the variation in input parameters for rural and urban areas.

Fig. 4 shows that the household monthly procurable electricity increases with an increase in monthly income share (spendable) on electricity, followed by the number of the first units that are sold at UgX 250 for both urban and rural areas. However, the household monthly procurable electricity decreases with an increase in the cost of the other electricity units above 15 kWh for both urban and rural areas. For the rest of the considered parameters, the monthly procurable electricity exhibits a slight decrease with an increase in any of them for both rural and urban areas. Overall, from Fig. 4 it is evident that the monthly procurable electricity is highly impacted by the variation in the monthly income share on electricity and the cost of the other electricity units above 15 kWh. To harness household affordability of the electricity, it is important to revise the tariff rate for the electricity units above the first 15 kWh which are subsidized. Likewise, households should be sensitized on the benefits of electricity and persuaded to increase their monthly income share dedicated to procuring electricity.

Fig. 5 shows the sensitivity of the duration to clear the initial electricity connection fee to the variation in input parameters. Fig. 5 shows that for both urban and rural households, the duration to clear the initial connection fee by a household increase with an increase in the initial connection fee. Thus, the higher the initial connection fee is, the longer the duration to save enough funds by the household from its monthly income to clear it for both urban and rural areas is. On the other hand, the duration to clear the initial connection fee decreases with an increase in the household monthly income and monthly income share on electricity. Thus, for a household to save enough funds to be connected to the power grid, it must either take on more income generating activities or dedicate more of its monthly income on electricity for both rural and urban areas. Overall, it is evident from Fig. 5 that lowering the initial connection fee would yield the shortest duration for households to clear them compared to monthly income and monthly income on electricity. This occurrence aligns with the fact that when government rolled out free connection to power grid, several households embraced it and were connected IEA, 2019 and 2020 (Ojok, 2021). Hopefully, the government shall devise means of budgeting for the necessary funds necessary to revamp the electricity connection policy to offer free electricity connection to households.

4.3. Alternative household electricity billing schemes

In assessing the utility revenue collection for the alternative

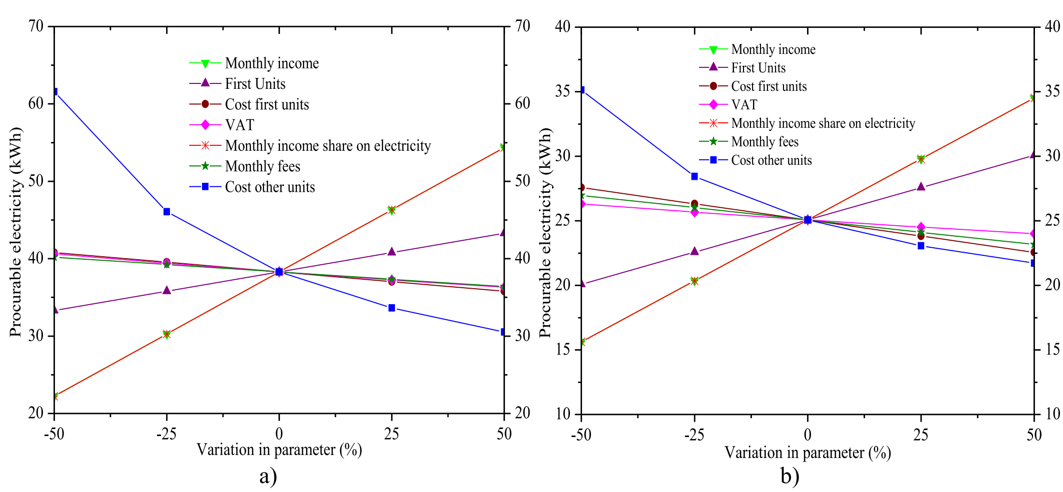

Fig. 4. Sensitivity of monthly procurable electricity by a household: a) Urban; b) Rural.

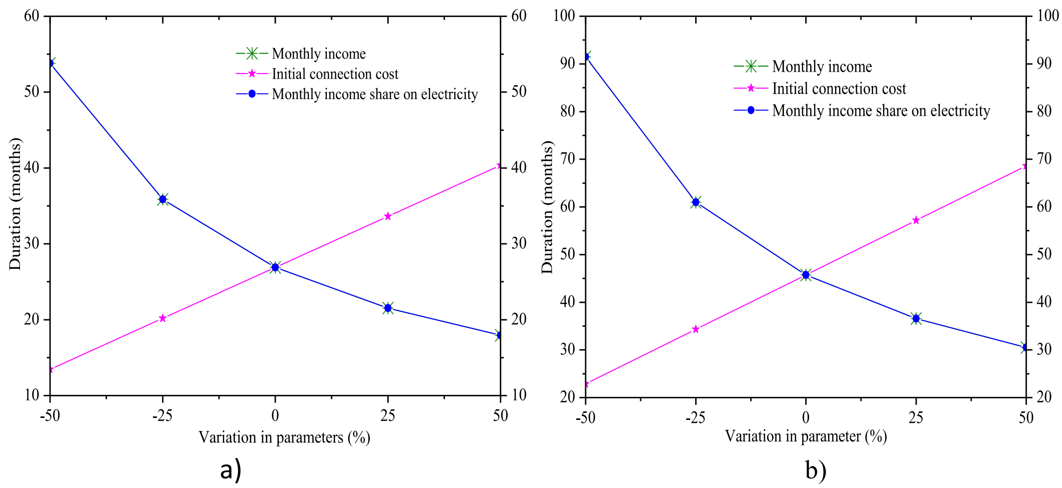

Fig. 5. Sensitivity of duration to clear initial cost: a) Urban; b) Rural.

household electricity billing schemes in Table 6, the assumed household monthly electricity consumptions of 30 kWh and 45 kWh for rural and urban areas, respectively, were considered. The charges for the alternative household electricity billing schemes in Table 6 were applied to Eqs. (9) and (10) for the urban and rural household, respectively, to determine the possible revenue collection for the utility. Fig. 6 show the monthly utility revenue collection for the considered alternative electricity billing schemes.

Fig. 6 shows that for both urban and rural households, the utility revenue collected is highest under Scenario A, the currently existent billing scheme in Uganda. The pattern for utility revenue collected differs for the other scenarios for urban and rural households. For instance, for urban households, the Scenario D is the second billing scheme with the highest utility revenue collected, followed by Scenario C and Scenario B. However, for rural households, Scenario B is the second billing scheme with the highest utility revenue collected, followed by Scenario C and Scenario D. For the urban household in Fig. 6 a), Scenario D comes second while Scenario B comes last because for Scenario B, most of the household electricity consumed (i.e., 40 kWh) are billed at UgX 450 and only 5 kWh are billed at UgX 747.5, plus VAT and monthly standard service fee, while for Scenario D, only 15 kWh of the household electricity consumed is billed at UgX 250 and the rest (i.e., 30 kWh) are billed at UgX 747.5, plus VAT. Therefore, Scenario D yields more utility revenue collected than Scenario B for the urban household. For the rural household in Fig. 6 b), Scenario B comes second, while Scenario D comes last because for Scenario B, all the household electricity consumed (i.e., 30 kWh) are billed at UgX 450, plus VAT and monthly standard service fee, while for Scenario D, 15 kWh are billed at UgX 250 and the other 15 kWh are billed at UgX 747.5, plus VAT. Therefore, Scenario B yields more utility revenue collected than Scenario D for the rural household. Thus, to harness electricity affordability by households, Scenario B is the appropriate billing scheme for urban households, while Scenario D is the appropriate billing scheme for the rural households based on the estimated monthly household electricity consumption in this analysis for these households in Uganda. Thus, as asserted in (Yakubu et al., 2018) that lowering electricity tariffs propels customers to pay their electricity bills, it is appropriate that the utility in Uganda considers alternative electricity billing schemes that would offer lower tariff rates but still guarantee economic feasibility to the utility.

For Uganda to achieve the targeted electricity tariff of 5¢$/kWh by 2025 (NPA, 2020; IGC, 2020), an equivalent of UgX 180 per unit of electricity will necessitate significant revision of the current electricity billing scheme in order to ensure viability of electricity transaction by the utility operators in the country. Also, to achieve the 60% access to electricity by the population and 90% reliability of electricity grid (NPA, 2020; IGC, 2020), extensive implementation of decentralized generation through micro-grid and mini-grid networks to exploit the abundant available renewable energy across the country will mitigate the costs of extending electricity transmission and distribution networks to far off areas (ERA, 2022; IGC, 2020; NPA, 2013). Such decentralized networks

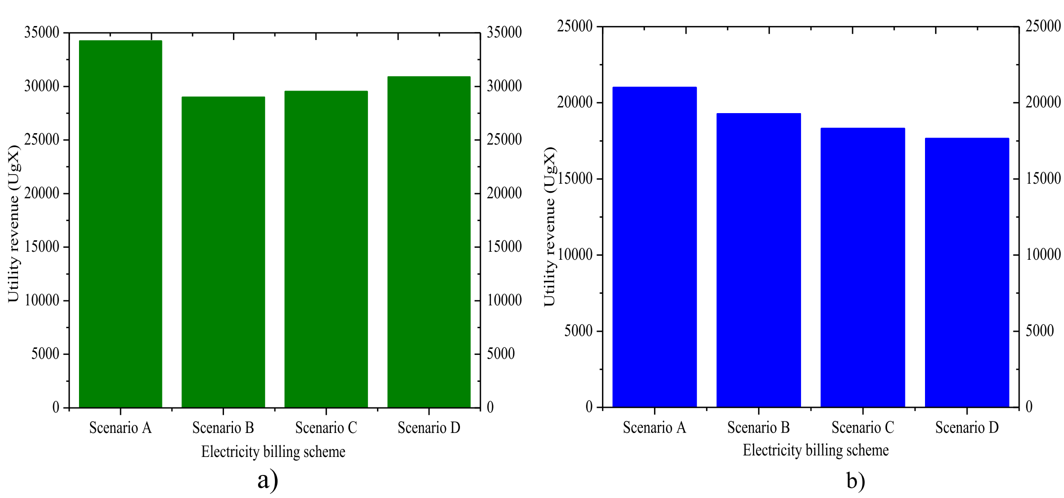

Fig. 6. Utility revenue collection for the different electricity billing schemes: a) Urban; b) Rural.

will play a crucial role in achieving the 80% connectivity of households to electricity networks by 2040 (IGC, 2020; NPA, 2013).

The results in this study indicate that Uganda ought to revise its energy policy to ensure that distributed electricity generation is optimized and the electricity tariffs are scaled down to ensure electricity affordability by households. Likewise, incentives, such as tax exemption to distributed electricity producers from mini-grids should be adopted. Supervision and enforcement of the Electricity Amendment Bill 2022

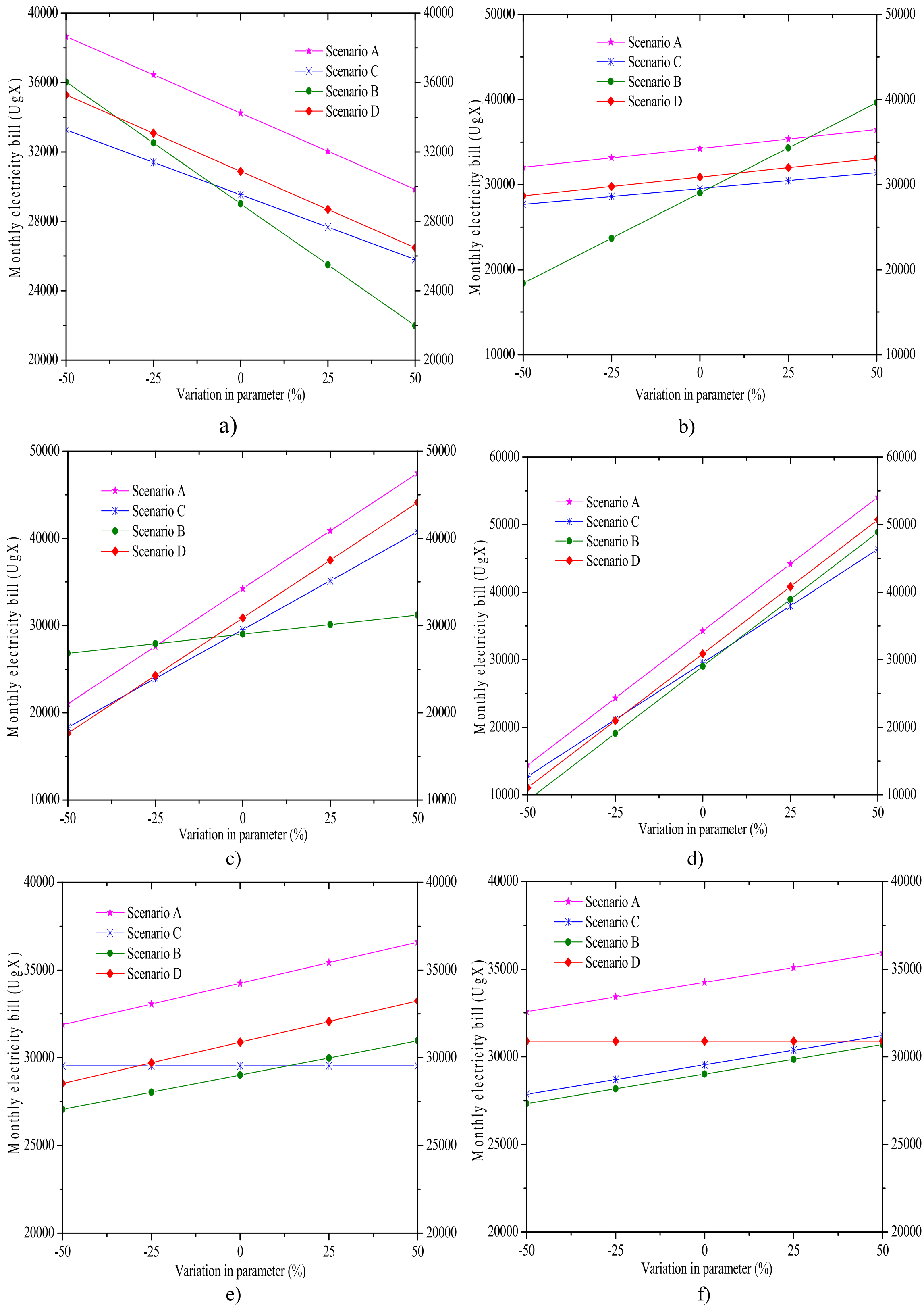

Fig. 7. Sensitivity of the monthly utility revenue collected: a) Subsidized Units; b) Cost of subsidized units; c) Cost of unsubsidized units; d) Monthly household electricity consumption; e) VAT; and f) Monthly standard service fee, for the urban household.

(UMEME, 2022a) fines for electricity theft and vandalism should be prioritized in order to minimized the occurrence of these vices.

4.3.1. Sensitivity analysis of the alternative household electricity billing schemes

To ascertain how the alternative household electricity billing scheme responds to the variations to the input parameters, a sensitivity analysis was undertaken for the case of the urban household. The utility revenue collected for all the alternative household electricity billing schemes in this study was assessed for its sensitivity to the variation in the input parameters in the range ±50%. Fig. 7 shows the sensitivity analysis of the alternative electricity billing schemes for the case of the urban household.

Fig. 7 a) shows that the utility revenue collected decreases with an increase in the number of household subsidized units, where the highest variation is registered for Scenario B. This is because for Scenario B, increasing the number of subsidized electricity units would result in all the household electricity consumed to be under the subsidized category of electricity units. Fig. 7 b) shows that the utility revenue collected increases with an increase in the cost of the subsidized units, where the highest variation is registered for Scenario B. This is because for Scenario B, increasing the cost of the subsidized electricity units would result in a higher billing for most of the household electricity consumed. Fig. 7 c) shows that the utility revenue collected increases with an increase in the cost of the unsubsidized electricity units, where the least variation is registered for Scenario B. This is because Scenario B has the fewest electricity units in the unsubsidized electricity category of all the alternative electricity billing schemes. Fig. 7 d) shows that the utility revenue collected increases with an increase in the monthly household electricity consumption, where the least the variation is registered for Scenario C. This is because the increase in the monthly household electricity consumption highly contributes to the VAT attributes for the scenarios except for Scenario C that does not have VAT included. Fig. 7 e) shows that the utility revenue collected increases with an increase in the VAT rate considered, except for Scenario C that registers no impact of VAT. This is because Scenario C does not have VAT as one of its input parameters for billing household electricity. Fig. 7 f) shows that the utility revenue collected increases with an increase in the monthly standard service fee, except for Scenario D that registers no impact of monthly standard service fee. This is because Scenario D does not have monthly standard service fee as one of its input parameters for billing household electricity. Overall, Fig. 7 shows that utility revenue collected is highly sensitive to the variation in the monthly household electricity consumption for all the alternative household electricity billing schemes in this study.

5. Conclusion and policy implications

Uganda has several targets for electricity accessibility, reliability, and affordability. However, these targets are facing several challenges, particularly from the household end-users. To ascertain the state of electricity security in Uganda, this study examined the household electricity affordability by using a probabilistic method to quantify households into categories for urban and rural areas. Specifically, household data for monthly income, electricity consumption, electricity tariffs, and initial connection fees were utilized to ascertain the household affordability of electricity. The current electricity billing scheme was used to establish the quantity of electricity units a household could afford based on its monthly income spendable on electricity. Further, this paper assessed the time it could take a household to save the required amount of money to legally be connected to the power grid. Finally, alternative billing schemes to enhance household electricity affordability were proposed and evaluated.

Findings indicate that based on the monthly household income spendable on electricity in Uganda, a significant proportion of the households cannot afford to pay for their electricity consumption. This observation provides four (4) compelling policy implications: First, to mitigate against electricity theft, it is crucial that the energy policy is revised to include incentives targeting domestic electricity consumers below a set number of electricity units. An adjustment of the existing electricity tariffs and on the relatively high initial connection costs could induce electricity connectivity by households, increase national electricity access rates, and improve electricity security. In the medium term, this policy could reduce on non-technical electricity losses when more households are legitimately connected to the grid.

Second, the government should revamp the suspended electricity connection policy 2018, which targets free electricity connection to households. This policy, if re-introduced and sustained, could set the country to achieve its electricity accessibility, reliability, and affordability targets by 2025 and 2040. The sustainability of this option, however, implies that additional investments in decentralized electricity generation through micro- and mini-grid networks are needed. This investment plan is suggested on the basis that Uganda has unexploited electricity production potential from the available hydro, solar, geothermal, and biomass energy resources. Third, to safeguard against electricity theft, the national energy policy should be revised to incentivize mini-grids' development in the country. This policy option could supply relatively affordable electricity for households in Uganda.

Finally, electricity utilities in Uganda register high losses to rural households due to the high tendencies of illegal tapping of electricity in rural areas that emanate from the low surveillance of these areas. With the Electricity Amendment Bill (2022), the government should intensify grid surveillance and have the offenders charged and sentenced before courts to minimize these vices. However, given that punitive interventions as theft-combat options, alone, do not completely eliminate electricity thefts, investment in social behaviour change of communities could gradually reduce electricity thefts. Thus, utility operators, through public awareness, should intensify campaigns on: a) the dangers of electricity theft to the life and livelihoods of households, and b) the contribution of legitimate electricity connection and use towards the progress of national economy.

This paper leans on a single dimension of electricity security - affordability. This implies that these findings can not employed to generalize and characterise Uganda's electricity security profile in entirety. In addition, the strength of the probabilistic approach utilized in this study is the ability to replicate the findings in a different setting or energy jurisdiction. However, on account of contextual differences, qualitative evaluation of the socio-economic and psychological factors that propel electricity theft in Uganda could add a superior perspective. Therefore, extending this analysis to other dimensions of electricity security, besides affordability should be considered. Further, other alternative electricity billing schemes should be investigated for suitability in Uganda to ensure feasibility to the utility and affordability to the households.

CRediT authorship contribution statement

Benard M. Wabukala: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, preparation, Visualization. **Nicholas Mukisa:** Methodology, Formal analysis, Investigation, Writing – original draft, preparation, Visualization, Supervision. **Susan Watundu:** Resources, Writing – review & editing, Supervision. **Olvar Bergland:** Resources, Writing – review & editing, Supervision. **Nichodemus Rudaheranwa:** Resources, Writing – review & editing, Supervision. **Muyiwa S. Adaramola:** Resources, Writing – review & editing, Supervision, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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