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Off-grid households' preferences for electricity services: Policy implications for mini-grid deployment in rural Tanzania

Cheng Wen[a,b,*], Jon C. Lovett[a], Emmanuel J. Kwayu[c], Consalva Msigwa[d]

[a] School of Geography, University of Leeds, Leeds, LS2 9JT, UK
[b] Research Institute of Environmental Law, Wuhan University, Wuhan, 430072, China
[c] Dar es Salaam University College of Education, P. O. Box 2329, Dar es Salaam, Tanzania
[d] Department of Electrical Engineering, Dar es Salaam Institute of Technology, P. O. Box 2958, Dar es Salaam, Tanzania

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ABSTRACT

Mini-grids play a critical role in providing electricity to remote, off-grid communities in Sub-Saharan Africa. However, success of mini-grid projects can be hindered by poor cash flows and limited revenue returns. A clear understanding of off-grid households' preferences for electricity services is a prerequisite for mini-grid stakeholders to set tariff structures and stimulate income-generating power demand to scale up mini-grid deployment. This study conducted a choice experiment survey in two off-grid villages targeted by new mini-grid projects in Tanzania to reveal heterogeneity in households' preferences for multiple electricity service attributes. We found that households' heterogeneous preferences were significantly associated with demographic (e.g. gender), socioeconomic (e.g. ownership of TV), and energy-related behavioural characteristics (e.g. charging devices away from home). We suggest that service-based, tiered tariffs and business models can be designed to cater for the heterogenous demands and preferences of different segments of customers. Successful deployment of mini-grids needs to consider the competition from the existing solar home systems and focus on the provision of higher tiers of electricity services. Gender equality issues should be addressed in rural electrification efforts given the significantly greater vulnerability of female-led households to higher electricity fees.

1. Introduction

The United Nations' Sustainable Development Goal 7 (SDG7) aims to achieve universal access to affordable, reliable, sustainable and modern energy by 2030 (UN, 2021). Although the global electrification rate rose from 83% to 90% during 2010–2019, there are still 759 million people without access to electricity around the world, three-quarters of whom (570 million) live in Sub-Saharan Africa (IEA, IRENA, UNSD, World Bank, WHO, 2021). It is estimated that the current pace of electrification will fail to achieve SDG7 worldwide, leaving 660 million people without electricity access in 2030 (IEA, 2020; IEA, IRENA, UNSD, World Bank, WHO, 2021).

Decentralized, renewable energy-based electrification solutions, such as solar-based (and hybrid) mini-grids, have been playing an increasingly important role in providing electricity to off-grid households in remote, rural areas where population densities are low and the cost of expanding national power grids is high (World Bank, 2017). The number of people served by mini-grids increased from 5 million to 11 million in the last decade (IRENA, 2020), however, many challenges have hindered the scale and speed of mini-grid deployment (Bhattacharyya, 2018; Bukari et al., 2021; MGP, 2020; Schnitzer et al., 2014; World Bank, 2017). One of the greatest challenges is the difficulty of maintaining adequate cash flows and revenue returns that can sustain mini-grid projects without continuous public funds/subsidies or international aid/donations (MGP, 2020; Williams et al., 2015).

Information about potential customers' WTP for electricity, their preferences for the duration of daily supply, electrical appliances to use, acceptable frequency of power-cuts, and other attributes regarding the quality of electricity services are essential for estimating electricity demand and potential revenue from tariff collection and thus the economic viability of mini-grid projects (ESMAP, 2019; USAID, 2018). A better understanding of off-grid households' preferences and WTP can help mini-grid developers to design mini-grid systems with service-based tiered tariffs to cater for the needs of a wider range of customers, from well-off households who are willing to pay higher tariffs for using productive appliances (e.g., refrigerators and milling machines) to poor

* Corresponding author. School of Geography, University of Leeds, Leeds, LS2 9JT, UK.
E-mail addresses: c.wen@leeds.ac.uk (C. Wen), j.lovett@leeds.ac.uk (J.C. Lovett), ejkwayu@gmail.com (E.J. Kwayu), msigwaj34@gmail.com (C. Msigwa).

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households who prefer basic electricity service at a low price for lighting bulbs and charging cell phones only (Wen et al., 2022). With more customers being connected to the mini-grids and their electricity demand stimulated by well-designed power services and tariffs, it is more likely to secure the revenue and financial return of mini-grid projects.

This study investigates off-grid households' preferences for electricity services in terms of four attributes highly relevant to the context of off-grid areas in Sub-Saharan Africa, namely daily supply hours, frequency of unplanned power-cuts, diversity of useable appliances (indicating the peak power capacity), and monthly electricity fees. The study site is in Tanzania, which has the fifth largest population (36 million) without electricity access in the world (IEA, IRENA, UNSD, World Bank, WHO, 2021). Only a quarter of its rural population had electricity supply (MGP, 2020). A case study in Tanzania could provide insights transferrable to Sub-Saharan Africa, as well as other countries with high access-deficits and great needs for mini-grids. A choice experiment survey was conducted in two Tanzanian off-grid villages targeted by new renewables-based mini-grid projects. Random parameter logit models and latent class models were applied to reveal the effect of various demographic, socioeconomic, and electricity-related behaviour characteristics on households' preferences for electricity service attributes.

2. Research method

2.1. Survey implementation and household characteristics

This survey was conducted in two Tanzanian villages (Fig. 1) with recently installed mini-grid projects. Kibindu Village, with about 350 households (2500 people), is in Chalinze District, Coastal Region, about 250 km from Tanzania's largest city Dar es Salaam. A 24-kW solar mini-grid has been built in Kibindu to serve the ward and village government offices, a primary school, a health centre, and 60 households. Another 20-kW gas-fired power generation unit has been built but is not in use yet because the current demand for electricity in the village has not exceeded the capacity of the solar grid. Luxmanda Village, with 489 households (3000 people), is in Bahati District of Manyara Region, about 850 km from Dar es Salaam. A 25-kW hybrid (solar + wind) mini-grid has recently been built in Luxmanda and supplies power to a secondary school, the village government office and dispensary, but no households were connected yet at the time of this survey. The current customers only consumed about 3% of the generated power from the mini-grid in Luxmanda. These two villages provide typical examples of off-grid communities where newly developed mini-grid systems have not yet reached their full potential to benefit local households. A better understanding of households' preferences for improved electricity access can provide useful information about successful deployment and management of mini-grids in the future.

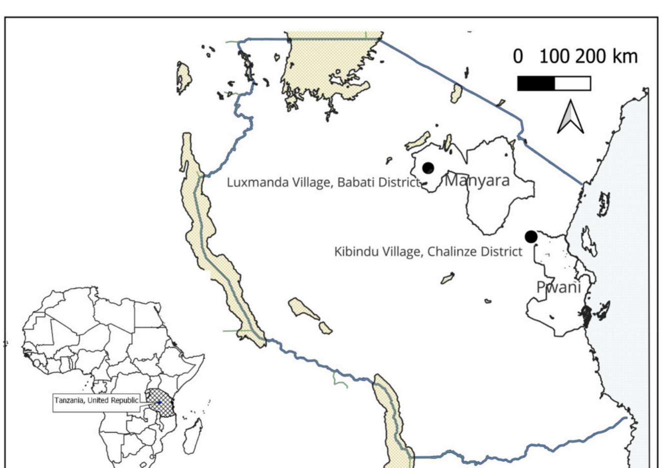

Fig. 1. Locations of sampled villages in Tanzania.

A total of 318 households were interviewed with structured questionnaires in the two study villages, 162 households in Kibindu (accounting for 46.2% of the total households in the village) and 156 households in Luxmanda (32.1% of the total households). The sample size has followed Orme (2014)'s calculation method and Mariel et al. (2020)'s rule of thumb suggestion about the minimal sample size required to obtain valid estimation for choice experiment studies. A preparatory fieldwork and pilot survey was made in the two villages to establish contact with district and local governmental officers and village leaders, test the questionnaire and collect relevant background information.

The main survey was conducted in Nov–Dec 2019 by a team of junior researchers from University of Dar es Salaam. In each village, the main survey started with an introductory group discussion with local informants (e.g. village chairperson) to explain the aim of the research, the survey plan and assistance needed from them. After discussing the plan and modality of the survey, the local informants introduced enumerators to randomly selected households for interviews. Different enumerators started the survey in different locations (e.g. the east end and the west end) of the villages and then skip the next nearby household after finishing the interview with each household. During the survey, the local informants were consulted to help ensure that the survey covered households in different socioeconomic backgrounds (e.g. reminding about certain locations resided by well-off or poor households but had not been visited by the enumerators). In Kibindu Village, 24 out of the 60 households connected to the current hybrid mini-grid were interviewed in this survey. The survey targeted the heads of households or their spouses if they were not around at the time of interviews.

Table 1 presents the descriptive statistics of household demographic and socioeconomic characteristics and the significance of difference between the two villages. Over 70% of respondents in both villages are

Table 1
Descriptive statistics of household characteristics.

Characteristic		Kibindu	Luxmanda	P-value [a]
Gender (male)		72.2%	79.5%	0.1670
Age [b]	Below 30	12.3%	14.7%	0.0095 **
	31–40	25.9%	24.4%	
	41–50	27.8%	29.5%	
	51–60	12.3%	22.4%	
	Above 60	21.6%	9%	
Education	Below primary school	17.9%	12.8%	0.5474
	Primary school	69.8%	72.4%	
	Secondary school	9.3%	12.2%	
	College	3.1%	2.6%	
Average family size		5.0	6.4	6.80E-6 ***
Average annual income (million TZS) [b]		3.224	2.768	0.1793
Labour hiring (yes)		17.3%	14.1%	0.5320
Motorbike ownership (yes)		19.1%	23.7%	0.3901
Mini-grid users		14.8%	0%	5.21E-08 ***
Solar home system		25.9%	61.5%	3.13E-10 ***
Charging devices elsewhere		47.5%	41.7%	0.3479
Non-electric lighting		10.5%	7.1%	0.3761
Use of Appliance	Cell phone	77.2%	83.3%	0.2150
	Lighting bulb	42.6%	60.9%	0.0016 **
	TV	11.1%	9.6%	0.8000
	Fridge	3.1%	0%	0.0608

[a] P-value of the significance of difference between the two villages. T-tests were applied to compare the means of numerical variables, while chi-square (or Fisher's exact) tests were applied test the independence between categorical variables and villages (significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1).

[b] Annual household income was calculated based on seven biggest income sources reported by respondents.

male heads of households. Households in the two villages have similar age distributions below 50. But for households aged over 50, there are about 10% more households aged between 50 and 60 (22.4% vs 12.3%) in Luxmanda, while 10% more households age above 60 (21.6% vs 9%) in Kibindu. About 70% of respondents in the two villages finished primary school as their highest education, and less than 5% of respondents have received college education. On average, households in the two villages have five and six family members, respectively. The average annual household income is about 3 million TZS (Tanzania Shilling) and the income disparity between the two villages is not significant.

Around 15% interviewed households in the two villages hire labour for farming or other activities, while around 20% households own at least one motorbike. 14.8% of the interviewed households in Kibindu Village are connected to a mini-grid power system as mentioned in Section 2.1, whereas no households in Luxmanda Village are mini-grid users. However, more than 60% of Luxmanda households have installed solar home systems, which is more than double of the figure of Kibindu Village (25.9%). Households in the two villages rely on multiple energy sources as nearly half of them charge their electric devices at nearby kiosks, and around 10% of households use non-electric lighting sources like kerosene and candles.

In terms of the use of electric appliances, around 80% of households in the two villages use cell-phones. Nearly half (42.6%) of Kibindu households use lighting bulbs at home, compared to 60.9% in Luxmanda Village. Only around 10% households in the two villages use a TV, and fridge users account for as few as 3.1% households in Kibindu. These descriptive statistics show that the interviewed households in this study offer a sample of typical off-grid households with rather limited access to relatively low quality of electricity supply in Tanzania, and to a wider context, in Sub-Saharan Africa.

2.2. Design of choice experiment

This study adapted four attributes from the World Bank's Multi-Tier Framework for assessing household electricity access (Bhatia and Angelou, 2015) to design a choice experiment: namely daily supply hours, frequency of unexpected power-cuts, diversity of useable appliances, and monthly electricity fees. The levels of the four attributes (Table 2) were decided based on information collected in the preparatory fieldwork and pilot survey. The attribute of "unplanned power-cuts" refers to unscheduled power-cuts due to malfunction issues. The attribute of "diversity of useable appliances" indicates the peak capacity (voltage) for running various appliances. Fixed monthly electricity fees, instead of the price per kWh, was adopted as the monetary attribute as it is easier for respondents to understand and make decisions.

Following the orthogonal fractional factorial experiment design method (Aizaki, 2012; Louviere et al., 2000), a total of 36 choice cards (sets) were generated and divided into three blocks. So, each respondent answered one block of 12 choice cards, and the order of choice cards were randomized in the survey. Table 3 shows an example of the choice cards with three options, two options of power service defined by four attributes at varied levels and an opt-out option of "None of them". Choosing this opt-out option indicates that the respondents are relatively satisfied with the status quo of electricity access. In each village, an approximately equal number of respondents were randomly assigned to one of the three blocks. A brief explanation was provided to the respondents before presenting the choice cards to help them understand the task and remind them to avoid overestimation of their WTP. In addition to the choice cards, questions about various household characteristics were asked in the questionnaires to help understand how these characteristics might influence households' preferences for electricity service attributes.

Table 2
Attributes and levels of power supply quality.

Attribute	Attribute Levels
Daily supply hours	6 h, 12 h, 24 h
Unexpected Power-cut	No power-cut at all, Once-a-week, Twice-a-week
Diversity of useable appliances	*Low:* lighting bulb and cell phone charger. *Medium:* all appliances above plus TV, DVD, computer, laptop, stereo speaker, blender and refrigerator. *High:* all appliances above plus wash machine, air conditioning, hair dryer, electrical kettle and cooker.
Monthly electricity fees	TZS[a] 7500; TZS 15,000; TZS 30,000; TZS 60,000

[a] TZS: Tanzania Shilling (TZS 2300 ≈ $1).

Table 3
An example of choice cards.

Attribute	Option 1	Option 2	None of them
Daily supply hours	6 h	12 h	
Unexpected Power-cut	No power-cut at all	Once a week	
Diversity of useable appliances	Lighting bulb and hand-phone charger	Lighting bulb and cell phone charger + TV, DVD player, computer, laptop, stereo speaker, blender, and refrigerator	
Monthly electricity fees	TZS 7500	TZS 15,000	
Pleas tick your preferred choice			

2.3. Econometric models

The Choice Experiment method is underpinned by the Characteristic Theory of Consumption (Lancaster, 1966) and the Random Utility Theory (Louviere et al., 2000; McFadden, 1974). It assumes that people derive utility from characteristics (attributes) of goods/services and make their choices to maximize the utility derived from the goods/services. When a respondent is asked to choose the preferred alternative (option) from a choice set (card), the utility of alternative i (U_i) is assumed to be composed of a deterministic, observable component V_i and a random unobservable error component ε_i, i.e. $U_i = V_i + \varepsilon_i$. The deterministic component V_i is usually assumed to be a linear function of the attributes vector X_i and the coefficients vector β, i.e. $V_i = \beta X_i$.

There are four electricity service attributes in this study. Daily supply hours (HOUR) and monthly electricity fees (FEE) are continuous variables, while unplanned power-cuts (P_cut) and diversity of useable appliance (APP) are categorical variables both with three levels. For the two categorical variables, the first level is treated as the base level and the other two levels are treated as binary dummy variables. Therefore, the utility function of this study is:

$$U_i = \beta_0 * \text{ ASC} + \beta_1 * \text{HOUR} + \beta_2 * \text{FEE} + \beta_3 * \text{P}_{\text{cut}} \text{ (once} - \text{a} - \text{week)} + \beta_4 * \text{P\_cut (twice} - \text{a} - \text{week)} + \beta_5 * \text{APP(medium)} + \beta_6 * \text{APP (high)} + \varepsilon_i \tag{1}$$

ASC is the Alternative Specific Constant, which is coded as 0 if respondents choose the opt-out option ("None of them") in the choice cards, otherwise coded as 1. The basic Conditional Logit Model (CLM), which assumes that the random error components ε_i independently and identically follows Gumbel distribution, defines the probability of choosing alternative i from choice card t as (Louviere et al., 2000; McFadden, 1974):

$$\Pr(i) = \frac{\exp(\beta X_i)}{\sum_{j \in t} \exp(\beta X_j)}, (\text{i} \neq \text{j}) \tag{2}$$

Marginal WTP of non-monetary attributes, i.e. how much respondents are willing to pay for each unit change of the attributes, can be calculated as: WTP $= -\beta_{nm}/\beta_m$, where β_{nm} is the coefficient of the non-monetary attribute and β_m is the coefficient of the monetary attribute (namely monthly electricity fees in this study).

The CLM assumes that the preferences (indicated by the coefficients vector β) is homogenous among all respondents, which is often not the case in the real life. This study applied two advanced choice models to take account of the heterogeneity in respondents' preferences: the Random Parameter Logit Model (RPL) and Latent Class Model (LCM). The RPL allows the coefficients (parameters) of attributes β to randomly vary among respondents and follow certain statistic distributions. The most widely used distribution is normal distribution, which can be described by mean and standard deviation. A simulation based maximum likelihood estimation method is needed to determine the distributions of coefficients of RPL (Hanley et al., 2006; Ruto and Garrod, 2009; Train, 1998, 2009). Assume that respondent n chooses alternative i from choice card t, then the simulated log-likelihood (SLL) of the whole sample of N respondents' choice sequences over all choice cards T is:

$$SLL = \sum_{n=1}^{N} \ln\left[\prod_{t=1}^{T}\frac{1}{R}\sum\nolimits_{r=1}^{R}\frac{exp\left(\beta^{r|\theta}X_{nit}\right)}{\sum_{j\in t} exp\left(\beta^{r|\theta}X_{njt}\right)}\right] \tag{3}$$

R is the number of random draws to apply the simulation, $\beta^{r|\theta}$ is the rth draw of coefficients β from the given distribution θ. This study used the statistical software R and a special package "mlogit" to apply the simulation and estimation to find the means and standard deviations of the normal distributions of β that maximize the SLL. (Croissant, 2013; R Core Team, 2021). Moreover, the effect of various household characteristics on their preferences for electricity service attributes are investigated by introducing interaction terms between the attributes and various household characteristics into the utility function (Eq. (1)).

Latent Class Model is another advanced choice model to take account of the heterogeneity in respondents' preferences. It assumes that respondents can be grouped into a number of latent classes (segments) whereby preferences are homogeneous within each class but heterogenous between different classes (Boxall and Adamowicz, 2002; Greene and Hensher, 2003; Sarrias and Daziano, 2017). Assuming there are S latent classes (segments) of respondents, respondent n chooses alternative i from choice card t, then the log-likelihood function (LL) of the whole sample of N respondents' choice sequences over all choice cards T and across all latent classes S is:

$$LL = \sum\nolimits_{n=1}^{N} \ln\left[\sum_{s=1}^{S}\frac{\exp(\gamma_s Z_n)}{\sum_{s=1}^{S}\exp(\gamma_s Z_n)}\prod_{t=1}^{T}\frac{\exp(\beta_s X_{nit})}{\sum_{j\in t}\exp\left(\beta_s X_{njt}\right)}\right] \tag{4}$$

Z_n is the vector of respondent characteristics that determine probability of respondent n being in class s, γ_s is the class-specific vector of coefficients of respondent's characteristics, and β_s is the class-specific coefficients of electricity service attributes. The class-specific vectors of coefficients γ_s and β_s can be estimated by maximizing the LL. This study applied the "gmnl" R package for the estimation of latent class models (Sarrias and Daziano, 2017).

3. Research results

3.1. Households' preferences and marginal WTP for electricity service attributes

Estimation results of random parameter logit models for the two villages are presented in Table 4. Coefficients of all non-monetary variables were assumed to follow normal distributions, as determined by estimated means and standard deviations, among the respondents to account for the heterogeneity in their preferences for power quality attributes. The monetary attribute of monthly electricity fees was estimated with a fixed coefficient for the convenience of calculating the marginal WTP for those non-monetary attributes.

Table 4
Households' preferences and WTP for electricity service attributes.

Variables	Kibindu	Luxmanda
Means of Random Coefficients		
Alternative specific constant	0.160	−0.183
Daily supply hours	0.050 ***	0.030 ***
Power-cut: once a week	−0.364 ***	−0.423 ***
Power-cut: twice a week	−0.573 ***	−0.407 ***
Diversity of appliances: Medium	0.536 ***	0.048
Diversity of appliances: High	0.868 ***	0.513 ***
Monthly electricity fees	−0.058 ***	−0.030 ***
Standard Deviations (SD) of Random Coefficients		
SD_Daily supply hours	0.052 ***	0.044 ***
SD_Power-cut: once a week	0.179	0.229
SD_Power-cut: twice a week	0.675 ***	0.574 ***
SD_Diversity of appliances: Medium	0.566 ***	0.506 ***
SD_Diversity of appliances: High	0.672 ***	0.712 ***
Marginal WTP (10^3 TZS/month)		
Daily supply hours	0.861 (0.664, 1.074) [a]	1.008 (0.626, 1.441)
Power-cut: once a week	−6.314 (−9.798, −2.940)	−14.192 (−21.781, −7.008)
Power-cut: twice a week	−9.923 (−13.572, −6.420)	−13.661 (−21.275, −6.361)
Diversity of appliances: Medium	9.282 (5.650, 13.179)	n.s.
Diversity of appliances: High	15.040 (11.420, 19.027)	17.213 (10.348, 24.884)
Goodness of fit		
Log-likelihood	−1684.2	−1777.3
Akaike Information Criterion (AIC)	3392.386	3578.607

Statistically significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1.
[a] Values in parentheses are the 95% confidence interval.

The first section of Table 4 reports the estimated means of random coefficients. All power quality attributes (or attribute levels) have highly significant mean coefficients at the 0.001 level, except for the medium level of appliance diversity for households in Luxmanda Village. The signs (±) of the mean coefficients show that, understandably, households in general prefer longer power supply hours per day and greater diversity of useable appliances (indicating higher peak power capacity), while being averse to unplanned power-cuts and higher monthly electricity fees. For households in Luxmanda, only the high-level of appliance diversity has significant coefficient, implying that improving the power capacity from using lighting bulbs and phone chargers only (the base level) to using medium-power appliances (such as TVs) is not enough to make them significantly more willing to pay for electricity access, but the improved power capacity for using high-power appliances (such as air conditioners) would do.

The second section of Table 4 reports the estimated standard deviations of random coefficients. The high significance level of these coefficients indicates that different households' preferences for electricity service attributes are highly heterogeneous, except for their aversion to once-a-week unplanned power-cuts in both villages. The standard deviation coefficients of Kibindu Village are generally larger than that of Luxmanda Village (except for the high-level of appliance diversity), indicating that households in Kibindu showed greater degree of heterogeneity regarding their preference for improved electricity services.

The third section of Table 4 presents the marginal WTPs for electricity service attributes (in 10^3 TZS/month). On average, households in the two villages were willing to pay 861 TZS ($0.37)/month and 1008 TZS ($0.44)/month respectively for having each extra hour of power supply per day within the range of 6–24 h (the lower-bound and upper-bound of this attribute in the choice experiment). This means that extending daily supply hours by 12 h would increase households' WTP for electricity services by 10,332 TZS ($4.49)/month and 12,096 TZS

($5.26)/month in Kibindu and Luxmanda, respectively.

Households in the two villages showed negative WTP for unplanned power-cuts (Table 4). In other words, they were willing to pay higher monthly fees for more reliable power service (i.e. avoiding unplanned power-cuts). Kibindu households would pay 6,314 TZS ($2.75)/month and 9,923 TZS ($4.31)/month for avoiding once-a-week and twice-a-week unplanned power-cuts, respectively. In comparison, Luxmanda households were willing to pay similar amount of money, around 14,000 TZS ($6.09)/month, for avoiding once-a-week or twice-a-week unplanned power-cuts.

As for the diversity of useable electric appliances, Kibindu households were willing to pay 9,282 TZS ($4.04)/month and 15,040 TZS ($6.54)/month for improved power capacity for using medium-power and high-power appliances, respectively. In comparison, households in Luxmanda Village were only willing to pay higher electricity fees for improving appliance diversity from the low-level to high-level, and that improvement would increase their WTP for electricity access by 17,213 TZS ($7.48)/month.

Overall, households in Luxmanda Village showed higher WTP for improvement in all the electricity service attributes compared to households in Kibindu Village, though the overlapped 95% confidence intervals of those WTP values imply relatively low significance for the differences. Interestingly, Luxmanda households have lower average annual income than Kibindu households, though the difference is not significant (Table 3), indicating that income might not always be the determining factor of household WTP for improved electricity services in off-grid areas of Tanzania.

To explore the possible sources of the heterogeneity in households' preferences for electricity service, we applied: 1) random parameter logit models with interaction terms between electricity service attributes and households' characteristics, and 2) latent class models that classified households into latent classes based on their own characteristics and preferences for electricity service attributes.

3.2. Results of random parameter logit models with interaction terms

Tables 5 and 6 report the results of random parameter logit models with interaction terms between electricity service attributes and different households' characteristics. Only significant interaction terms that improve the overall goodness of fit are kept in the reported models for the two villages. If the coefficients of interaction terms have the same signs (±) with the mean coefficients of the electricity service attributes, households' preferences for the service attributes were reinforced (i.e. showing stronger preference or aversion) by the household characteristics. Otherwise, households' preferences/daversion for the service attributes were weakened by the household characteristics.

Interaction terms of household characteristics with the alternative specific constant (ASC) were introduced in the models to examine the effects of household characteristics on their general preferences for choosing electricity services proposed in the choice cards over the status quo (the opt-out option). Table 5 shows that the mean coefficients of ASC in the two models for Kibindu Village and Luxmanda Village are both positive (0.665 and 1.753), while the coefficients of the interaction terms of ASC with gender (female) are both negative (−0.696 and −0.719) and significant (at the 0.01 and 0.001 level). This indicates that female respondents in both villages were significantly less willing to choose the proposed electricity services in the choice cards and more likely to choose the status quo.

Age showed opposite effects on households' preference for ASC in the two villages. While older respondents in Kibindu Village were more likely to choose the proposed electricity service, their counterpart in Luxmanda Village were more likely to choose the status quo. Households with higher education levels in Kibindu and those with higher income in Luxmanda also showed weaker preference for the proposed electricity services compared to the status quo. Moreover, Kibindu households who charged their electrical devices (e.g. cell-phones) away from home (e.g. local kiosk providing charging services) showed stronger preference for the ASC, which indicates stronger willingness to pay for improved electricity access.

Three household characteristics (mini-grid users, age and income) were found to exhibit significant effect on households' preference for the

Table 5
Random parameter logit models with interaction terms (I).

Variables	Kibindu		Luxmanda	
Means of Random Coefficients				
Alternative specific constant (ASC)	0.665		1.753	***
Daily supply hours	0.054	***	0.039	***
Power-cut: once a week	−0.475	**	−0.988	***
Power-cut: twice a week	−0.306	*	−0.725	***
Diversity of appliances: Medium	1.585	***	−0.070	
Diversity of appliances: High	2.948	***	0.104	
Monthly electricity fees	−0.202	***	−0.132	***
Standard Deviations (SD) of Random Coefficients				
SD_Daily supply hours	0.036	***	0.034	***
SD_Power-cut: once a week	0.070		0.096	
SD_Power-cut: twice a week	0.520	**	0.056	
SD_Diversity of appliances: Medium	0.177		0.175	
SD_Diversity of appliances: High	0.545	**	0.513	**
SD_Monthly electricity fees	0.064	***	0.061	***
Interactions with ASC				
Gender (female)	−0.696	***	−0.719	**
Age	0.418	***	−0.534	***
Education	−0.644	***		
Income			−0.103	*
Charging devices elsewhere	0.745	***		
Interactions with daily supply hours				
Mini-grid users	0.052	***		
Age			−0.044	**
Income			0.004	*
Interactions with unplanned power-cuts				
Motorbike (once-a-week)	0.226			
Motorbike (twice-a-week)	0.756	**		
Income (once-a-week)	−0.015			
Income (twice-a-week)	−0.134	***		
Solar home system (once-a-week)			0.567	**
Solar home system (twice-a-week)			0.510	**

Statistically significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1.

Table 6
Random parameter logit models with interaction terms (II).

Variables	Kibindu		Luxmanda	
Interactions with diversity of appliances				
Age (medium)	−0.238	°		
Age (high)	−0.466	***		
Family size (medium)	−0.050			
Family size (high)	−0.098	*		
Income (medium)			0.061	°
Income (high)			0.125	***
TV (medium)			0.620	°
TV (high)			1.080	**
Charging devices elsewhere (medium)	−0.182			
Charging devices elsewhere (high)	−0.604	**		
Interactions with monthly electricity fees				
Gender (female)	−0.018	*		
Age			0.033	***
Education	0.021	***	0.022	***
Family size	0.004	***		
Income	0.005	***	0.002	*
Labour-hiring			0.024	***
TV			−0.024	*
Phone			0.005	**
Solar home system	0.043	***		
Charging devices elsewhere	0.015	*		
Non-electric lighting source(s)			−0.023	*
Goodness of fit				
Log-likelihood	−1513.4		−1809.6	
Akaike Information Criterion (AIC)	3094.75		3281.19	

Statistically significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1.

attribute of daily supply hours. Mini-grid users in Kibindu Village showed stronger preference for longer service hours. In Luxmanda Village, respondents older than 60 were less willing to pay for extending daily supply hours, while households with higher income were more willing to do that.

There are also three household characteristics (ownership of motorbikes, income, and solar home system users) that were significantly associated with households' heterogenous preferences for the attribute of unplanned power-cuts. In Kibindu Village, ownership of motorbikes and annual income showed opposite effect on households' preference for improved service reliability and both at the level of avoiding twice-a-week power-cuts only. Kibindu households owning motorbike(s) showed more tolerance to unplanned power-cuts, probably because better mobility made it easier for them to charge their essential devices (e.g. mobile phones) in nearby kiosks in the event of power-cuts. Meanwhile, Kibindu households with higher income were more averse to unreliable electricity service, in other words, more willing to pay for improved service reliability. In Luxmanda, households who have installed solar home systems were less averse to power-cuts, which means that they were less willing to pay for improvement in power reliability.

Table 6 presents the estimated coefficients of interaction terms of household characteristics with the other two electricity service attributes, namely diversity of useable appliances and monthly electricity fees. Age, family size and the experience of charging electronic devices elsewhere (away from home) were all associated with weaker preference for improved appliance diversity in Kibindu Village, but the effect was only significant at the level of using high-power appliances. In Luxmanda, households with TV and higher income were more likely to prefer improved diversity of useable appliances, and such stronger preference was also significant for the high-level of appliance diversity only.

A total of 11 characteristics were found to show significant effect on households' attitudes towards increase in monthly electricity fees. Higher education and income were both associated with less sensitivity to higher monthly electricity fees in both villages. In Kibindu Village, gender (female) is the only characteristic associated with stronger aversion to higher electricity fees, while larger household size, owning solar home systems and charging electric devices away from home were all associated with less aversion to higher expenditure on electricity. In Luxmanda Village, older respondents (above 60), labour-hiring and the number of cell-phones used by the households were associated with weaker aversion to higher electricity fees, whereas TV ownership and the use of non-electric lighting (e.g. kerosene, candles) were linked to stronger aversion to increased expenditure on electricity.

3.3. Results of latent class models

The latent class models examined the heterogeneity in households' preferences by grouping households into different classes (segments) based on their preferences and characteristics. In this study, household characteristics included in the final random parameter logit models with interaction terms for the two villages were used to estimate the latent classes models. There-class models were selected by comparing two-class, three-class and four-class models based on their AIC values and interpretability of the model results. For each village, Class 1 was taken as the baseline/reference class, so no coefficients of household characteristics were estimated. For the other two latent classes, the estimated coefficients of household characteristics indicate the effect of the characteristics on the likelihood of households being grouped into Class 2 or 3 (Table 7). Coefficients of electricity service attributes were estimated for each latent class.

Latent class models revealed some information overlooked by the random parameter logit models. For example, random parameter logit models indicate that households in Kibindu Village, on average, showed significant preferences for all electricity service attributes (Table 4), but latent class models revealed that there were different classes of households who showed rather different preferences. As reported in Table 7, Kibindu households in Class 1 show significant preference for all the electricity service attributes, but households in Class 2 did not show significant preference for the improvement of appliance diversity. Households with male heads (given the negative coefficient of female ones), higher education levels, larger family sizes, motorbike(s) and solar home systems were more likely to belong to Class 2. Moreover,

Table 7
Latent class models of households' preferences for electricity service attributes.

Variables of Electricity Access	Kibindu						Luxmanda					
	Class 1		Class 2		Class 3		Class 1		Class 2		Class 3	
Alternative specific constant (ASC)	1.004	**	0.275		0.886	**	−8.646		−0.302		0.706	**
Daily supply hours	0.088	***	0.040	***	0.057	***	0.305	***	0.056	***	0.020	**
Power-cut: once a week	−0.535	*	−0.645	**	−0.130		−0.822		−0.422	**	−0.367	**
Power-cut: twice a week	−0.902	***	−0.366	°	−0.335	°	−3.674	*	−0.335	*	−0.019	
Diversity of appliances: Medium	0.967	***	0.202		0.616	***	5.726		0.305	°	0.033	
Diversity of appliances: High	1.257	***	0.234		1.165	***	8.237		0.811	***	0.197	
Monthly electricity fees	−0.234	***	−0.042	***	−0.028	***	−0.426	***	−0.067	***	−0.008	*
Characteristics for Classification												
Intercept			−1.595	*	0.171				0.032		−0.351	
Gender (female)			−0.882	***	−0.772	***			−1.201	***	−1.701	***
Age			0.030		−0.163	*			1.388	***	1.524	***
Education			0.482	*	−0.177				0.240		0.342	*
Family size			0.215	***	0.042							
Income			0.024		0.065	**			0.149	***	0.133	***
Motorbike			0.571	**	0.579	**						
Labour hiring									9.548		9.892	
Mini-grid users			−0.487		0.008							
Solar home system			0.502	**	0.876	***			0.237		0.404	*
Charging devices elsewhere			0.024		0.789	***						
Non-electric lighting source(s)									6.317	*	5.308	°
TV									0.190		−0.327	
Cell-phone									−0.143	*	0.067	
Goodness of Fit												
Log-likelihood	−1521.1						−1595.9					
Akaike Information Criterion (AIC)	3124.2						3273.8					

Statistically significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1.

households in Class 3 were interested in improving electricity service in general but did not show significant preference for avoiding unplanned power-cuts. Similar to Class 2, Class 3 also tended to have male heads of households, motorbikes and solar home systems, but they were more likely to have higher income and the experiences of charging their devices in local kiosks or elsewhere away from home. It is also noteworthy that households in Class I, who tended to have female respondents (as Class 2 & 3 both tended to have male ones), were much more averse to increase in monthly electricity fees than the other two classes (coefficients −0.234 against −0.042 and −0.028).

In Luxmanda Village, households in Class 1 also tended to have female respondents (given the significant and negative coefficients of gender in the other two classes) and were much more averse to increase in monthly electricity fees than the other two classes (coefficients −0.426 against −0.067 and −0.008), but they did not show significant preference for avoiding once-a-week unplanned power-cuts or improving the diversity of useable appliance. In comparison, Class 2 households showed significant preference for all electricity service attributes (except the medium-level of appliance diversity at the 0.1 significance level), and they tended to have male, older respondents, higher income, and use non-electric lighting source(s) and fewer cell-phones. Households in Class 3 were more likely to choose the proposed electricity service in the choice cards over the status quo (given the significant coefficient of ASC) and much less sensitive to higher monthly electricity fees than the other two classes. Apart from that, Class 3 households showed similar attitudes towards improved electricity service to Class 1 in terms of having insignificant preference for greater appliance diversity and avoiding one of the two levels of unplanned power-cuts. With regard to the household characteristics of Class 3, they shared a similar profile to Class 2 households in terms of having male, older respondents, higher income, but they were more likely to have higher education and solar home systems compared to households in Class 1.

4. Discussion

4.1. Implied WTP and preference for mini-grid services

This study estimated off-grid households' WTP for extending daily supply hours, avoiding unplanned power-cuts, and improving the power capacity for using medium/high-power appliances in rural Tanzania. Although direct comparison between our results and that of other studies in Sub-Saharan countries is difficult due to differences in the socioeconomic contexts (e.g. different countries), targeted populations (urban or rural), and the exact attributes being estimated (e.g frequency or duration of unplanned or planned power-cuts), our results show some consistency with the others (Table 8). For example, Zemo et al. (2019) found that urban residents in Ethiopia were willing to pay up to $0.65/month for reducing one power-cut in a month, while households in the two village of this study were willing to pay $0.54-$0.76/month for that (equivalent to $4.31-$6.09/month for avoiding twice-a-week power-cuts).

It is worth noting that this study is the only one in Table 8 that estimated household WTP for improving the power capacity for using medium/high-power appliances. This attribute is particularly relevant to mini-grids because electricity services from pico-PV kits, solar home systems, and mini-grids may be similar in terms of daily supply hours and frequency of power-cuts, but they mostly differ in what appliances can be used with the services. Only mini-grids (and the main grids) are potentially capable of powering high-power appliances. This study found that households in the two villages were willing to pay $6.54-$7.48/month for improving the power capacity for using diverse appliances from low-power ones (bulbs and phones only) to high-power ones (wash machine, air conditioning, electric cooker, etc.), which implies that households were willing to pay that amount of money for upgrading services from pico-PV kits (or home solar systems) to mini-grids. The result is generally in line with Sievert and Steinbuks (2020)'s findings that the difference in households' WTP for solar home systems and grid services in Burkina Faso, Rwanda, and Senegal ranged between $2.51-$7.00/month.

Table 8
Household WTP for improved electricity services in different studies.

Study	Country	Urban/ Rural	Household WTP for Improved Electricity Services
Abdullah and Mariel (2010)	Kenya	Rural	51.79 KSh ($0.68)/month for reducing one planned power-cut (between 2 and 6 times) in a month.
Alinsato (2015)	Benin	Urban	$0.21–$1.9 for avoiding 1–8 h of unplanned power-cut in a day.
Taale and Kyeremeh (2016)	Ghana	Urban	$3.42/month for reliable electricity services.
Oseni (2017)	Nigeria	Both	$6.82/month for reducing power-cuts to half of its present level (72 h per week).
Nkosi and Dikgang (2018)	South African	Urban	$2.61-$6.08 for avoiding 2–5 h unplanned power-cuts.
Amoah et al. (2019)	Ghana	Urban	$17/month for 24-h electricity supply.
Zemo et al. (2019)	Ethiopia	Urban	1.86–18.57 Birr ($0.08-$0.65)/ month for reducing one power-cut (between 1 and 10 times/ month).
Meles (2020)	Ethiopia	Urban	$1.3-$1.5/month for avoiding all unplanned power-cuts (53 h per month).
Sievert and Steinbuks (2020)	Burkina Faso, Rwanda, Senegal	Rural	$4.49-$14.3/month for solar lamps, $7.13-$15.32/month for solar home systems, $9.64-$22.32/month for grid service
Meles et al. (2021)	Ethiopia	Urban	$0.4/month for reducing one power-cut (between 1 and 8 times) in a month.
Aweke and Navrud (2022)	Ethiopia	Both	$18/year ($1.5/month) for eliminating all power-cuts (160 times in a year).
This study	Tanzania	Rural	$4.49-$5.26/month for extending daily electricity supply by 12-h, $4.31-$6.09/month for avoiding twice-a week (i.e. 8 times/ month) unplanned power-cuts, $6.54-$7.48/month for improving the diversity of useable appliance from low to high.

In addition to the estimated WTP for the capacity of using high-power appliances, another way to infer households' acceptance to mini-grid services is to examine the percentages of households that show a positive preference for the high-level power capacity (i.e. appliance diversity). Based on the result of our random parameter logit models (Table 4), Kibindu households' heterogeneous preferences for the capacity of using high-power appliances followed a normal distribution with the mean of 0.868 and the standard deviation of 0.672. The likelihood of having a positive coefficient (preference) in such a normal distribution is 90.2%. This implies that 90.2% of households in Kibindu are likely to be mini-grid customers. Following the same analysis, we can infer that 76.4% of households in Luxmanda are likely to accept mini-grid services.

4.2. Tiered tariffs for tiered services

Recent research on mini-grid business models in rural Tanzania has suggested the use of differentiated tariffs for different categories of customers to facilitate greater adoption and sustained use of electricity services (Ogeya et al., 2021). In this study, households' WTP for different levels of improved electricity services and the existence of latent classes (segments) of households with heterogeneous preferences further imply the possibility of creating mini-grid business models that charge tiered tariffs for tiered electricity services.

Some tiered tariffs have been applied based on customers' preferences for individual electricity service attributes, such as the "power-based tariffs" which charge different groups of customers differently based on the peak power in watts (ESMAP, 2000; Franz et al., 2014; Tenenbaum et al., 2014) and the "service-reflective tariffs" recently introduced in Nigeria that charge different bands of tariffs to customers who receive different hours of services per day (Nweke-Eze, 2021). However, these existing tiered tariffs are not able to take account of customers' preferences for multiple attributes of electricity services.

It is worth noting that the four electricity service attributes used in this study was adapted from the World Bank's Multi-Tier Framework (MTF) for measuring household electricity access (Bhatia and Angelou, 2015; ESMAP, 2022). This MTF is increasingly applied to assist with the technical/engineering design of off-grid power systems (Elmorshedy et al., 2021; Few et al., 2022; Narayan et al., 2019b), but very few discussions have been found about its potential application in designing mini-grid tariffs and business models. Here we suggest that future research and deployment of mini-grids could apply or adapt the World Bank's MTF to design service-based, tiered tariffs because it provides a useful framework to address customers' preferences for multiple electricity service attributes. Choice Experiment studies based on the MTF can estimate customers' marginal WTP for improvement in individual attributes and then calculate the aggregate WTP for improving electricity services from lower tiers to higher tiers of the MTF (Wen et al., 2022). Such WTP information, together with techno-economic analysis of the cost of providing different tiers of electricity services, can help mini-grid developers to design the commensurate tiered tariffs. A complete exploration of the design of tiered tariffs is beyond the scope of this study but could be a promising direction for future research.

4.3. Potential competition between off-grid technologies

This study systematically examined the effects of various households' characteristics on their preferences for different attributes of electricity services. Income was found to be the only characteristic that showed significant effect on households' preferences for all the four attributes. It is understandable that higher income was associated with stronger demand for improved electricity services. However, a seemingly conflicting result is that higher income was associated with higher chances of choosing the status quo in Luxmanda Village. Similarly, higher education was also associated with higher chances of choosing status quo in Kibindu Village.

A possible explanation is that some households in the two villages were satisfied about the status quo of electricity services as over 60% of interviewed households in Luxmanda had installed solar home systems and more than 25% of interviewed households in Kibindu had done so. Higher education and income level could give households better access to these off-grid electrification technologies, which made them more likely to feel satisfied about the status quo. The implication for mini-grid developers here is that although higher income could be linked to higher demand for improved electricity services, new mini-grid projects need to consider the competition with the existing power solutions such as solar home systems. It should not be simply assumed that higher income and education levels would "naturally" lead to higher acceptance of new mini-grid projects.

The potential competition between mini-grids and solar home systems deserves attentions of researchers, practitioners, and policy makers. On one hand, the deployment of mini-grids may be less effective due to the presence of alternative power solutions. On the other hand, the newly installed mini-grids may turn the existing home solar systems into stranded assets, causing waste of previous electrification funds/subsidies (Aziz and Chowdhury, 2021). Here we suggest that mini-grids should aim to provide Tier 3–5 services in the MTF that support the productive use of high-power appliances (e.g., refrigerators, milling machines), while the market segment for elementary electricity services (Tier 1–2 in the MTF) can be served by solar home systems or pico-PV kits. The existing stand-alone home solar systems could also be connected to build new mini-grid systems to meet households' increasing power demand over time rather than becoming stranded assets (Narayan et al., 2019a).

4.4. Gender equality in mini-grid deployment

Gender equality and its linkage with energy access is an important issue in rural electrification as the benefits of improved energy access may not equally accrue to men and women. In this study, we found that female respondents were significantly less willing to choose proposed electricity services over the status quo in the choice experiment and more likely to belong to the latent classes with much stronger aversion to higher monthly electricity fees. This result implies that female respondents' stronger preference for the status quo does not necessarily mean that they are happy with the current electricity access. Instead, it is possible that they chose the status quo just because they could not afford improved electricity services with higher cost. In other words, female-headed households might have fewer opportunities to benefit from improved electricity access provided by the new coming mini-grids due to their significantly greater vulnerability to increased cost of electricity. We would like to suggest that mini-grid developers and policy makers should provide financial support for female-headed, low-income households to get access to mini-grid services. This will help to close the gender gap in electricity access and empower women to gain well-fare and development benefits through linkages between SDG7 and other sustainable development goals.

5. Conclusion and policy implications

This study conducted a choice experiment survey in two off-grid villages in rural Tanzania to investigate household preferences for electricity services in terms of daily supply hours, unplanned power-cuts, diversity of useable appliances (indicating the peak power capacity for using medium/high-power appliances) and monthly electricity fees. Based on the WTP and preferences for the power capacity of using high-power appliances, we found that households in the two villages were willing to pay an average of $6.54/month and $7.48/month respectively for upgrading services from pico-PV kits (or home solar systems) to mini-grids, and there are 90.2% of households in Kibindu and 76.4% of households in Luxmanda who are likely to be mini-grid customers. We also found significant heterogeneity in households' preferences for electricity service attributes, which were associated with demographic characteristics (gender, age, education, family size and income), socioeconomic conditions (labour-hiring, ownership of motorbikes, cell phones and TV), and energy consumption behaviours (mini-grid connection, installation of solar home systems, charging devices away from home, and using non-electric lighting).

Based on our research results, we would like to provide the following policy suggestions on mini-grids deployment in rural Tanzania and other Sub-Saharan African countries alike.

(1) Mini-grid developers could apply or adapt the World Bank's MTF of electricity access to design business models that charge tiered tariffs for tiered services to meet the demands of different segments of customers. Choice experiment is a useful tool to help design such tiered tariffs that take account of customers' heterogenous preferences for multiple electricity service attributes.
(2) Mini-grid developer, policy makers and other related stakeholders should consider the potential competition between mini-

grids and existing solar home systems. Mini-grids should aim to provide Tier 3 and higher tiers of electricity services in the MTF.
(3) To ensure that females' opportunities of benefiting from improved electricity access are not undermined by their greater vulnerability to increased electricity fees, financial support is needed to help female-headed, low-income households to get access to mini-grid services.

A major limitation of this study is that we could not link the WTP estimates of this socioeconomic survey with results of techno-economic analysis (such as LCOE from mini-grids) and accordingly conduct more in-depth exploration of the design of tiered tariffs. This interdisciplinary area will be the direction of our future research to provide more practical policy suggestions on mini-grid deployment in Tanzania and other Sub-Saharan countries.

CRediT authorship contribution statement

Cheng Wen: Conceptualization, Methodology, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Jon C. Lovett:** Funding acquisition, Supervision, Project administration, Writing – review & editing. **Emmanuel J. Kwayu:** Investigation, Data curation, Visualization, Writing – review & editing. **Consalva Msigwa:** Conceptualization, Investigation, Project administration.

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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