Energy Research & Social Science 88 (2022) 102503

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Household willingness to pay for improving electricity services in Sumba Island, Indonesia: A choice experiment under a multi-tier framework

Cheng Wen [a,b,*], Jon C. Lovett [a], Elisabeth Rianawati [c], Teresa R. Arsanti [c], Siti Suryani [d], Adi Pandarangga [e], Saut Sagala [f]

[a] School of Geography, University of Leeds, Leeds LS2 9JT, UK
[b] Research Institute of Environmental Law, Wuhan University, Wuhan 430072, China
[c] Resilience Development Initiative, Bandung, Jawa Barat 40135, Indonesia
[d] Wira Wacana Christian University, Sumba, Waingapu 87112, Indonesia
[e] East Sumba Local Development and Planning Agency, Sumba, Waingapu 87112, Indonesia
[f] School of Architecture, Planning and Policy Development, Bandung Institute of Technology, Ganesha 10, Bandung 40132, Indonesia

ARTICLE INFO

Keywords:
Rural electrification
Sustainable Development Goal 7
Power quality
Stated preference
Non-market valuation
Southeast Asia

ABSTRACT

Global efforts to improve electricity access in developing countries need to go beyond the simple measurement of electrification rates to address the quality of electricity supply. Households' preferences and willingness to pay (WTP) for electricity supply is important information for policy makers, utility companies, and other stakeholders to plan investment in power infrastructure, design business models, and tackle energy-related social equality issues. However, the existing literature is largely focused on consumers' attitudes towards green electricity, while preferences for improving the quality of electricity supply have not been fully researched, especially in the context of deprived areas in developing countries. Based on the World Bank's Multi-Tier Framework (MTF) for measuring energy access, this study conducted a Choice Experiment on the "Iconic Island" of Sumba in Indonesia to investigate households' preferences for four attributes of electricity access: daily supply hours, frequency of unplanned power-cuts, power capacity of using medium/high-power appliances, and monthly electricity fees. The results reveal that reduction of power-cuts, the most studied attribute of power supply in previous studies, is less significant than other attributes in Sumba. Households connected to the main-grid show higher WTP for improving electricity supply than off-grid households. Heterogeneity in households' preferences is significantly associated with gender, age, education level and household income. We discussed policy implications for penetration of renewable energy, prioritising electrification investment and designing service-based electricity tariffs. We also demonstrated the potential for further application of choice experiment results with the MTF of energy access.

1. Introduction

Global efforts have been made to improve energy access in low- and middle-income countries following the creation of United Nations' Sustainable Development Goal 7 (SDG7): to "ensure access to affordable, reliable, sustainable and modern energy for all" [1–3]. Traditionally, energy access is measured by the binary status of whether a household has access to specified energy supply or not. Such binary measurement does not take account of the quality of energy access. So, when electrification rates are calculated, households with intermittent electricity supply only sufficient for lighting in the evening would be placed in the same category as households with 24-hour continuous electricity supply capable of powering televisions, refrigerators, and high-wattage appliances. To overcome limitations of the simple, binary measurement of electrification rates, a multi-tier framework (MTF) has been developed by the World Bank to provide a graduated system for measuring the quality of energy access [4]. This MTF defines six levels (Tier 0 to Tier 5) of household electricity access based on seven attributes, including peak capacity, supply duration, reliability, voltage stability, affordability, legality, and health & safety. The formulation and adoption of this MTF

Abbreviations: WTP, Willingness to Pay; MTF, Multi-Tier Framework; CLM, Conditional Logit Model; RPL, Random Parameter Logit.

* Corresponding author at: 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), elisabeth.rianawati@rdi.or.id (E. Rianawati), teresa.arsanti@rdi.or.id (T.R. Arsanti), sitisuryani.asmikro@gmail.com (S. Suryani), benpandarangga@gmail.com (A. Pandarangga), saut.sagala@sappk.itb.ac.id (S. Sagala).

https://doi.org/10.1016/j.erss.2022.102503
Received 27 April 2021; Received in revised form 30 November 2021; Accepted 5 January 2022
Available online 22 January 2022

to evaluate and monitor the progress of rural electrification in developing countries underlines the need for addressing the quality of electricity supply beyond increasing electrification rates [1,5].

Households' preferences and willingness to pay (WTP) for electricity supply is important information for policy makers, energy companies and other stakeholders to plan investment in power infrastructure, design business models, and tackle energy-related social equality issues. This is particularly relevant for countries/regions with low levels of electrification where off-grid electricity solutions like mini-grids highly depend on a tight economic linkage between electricity producers and consumers because it is usually more difficult to allocate government subsidies to small-scale power grids compared to large-scale projects [6–8]. The existing literature on households' WTP for electricity supply is mainly focused on consumers' attitudes towards green/renewable electricity [9–15]. Only a small group of studies have investigated WTP for improving the quality of electricity supply, which largely concentrates on attributes related to power reliability (reduction of power-cuts) in developed countries or urban areas of developing countries [16–21]. Other power quality attributes, such as daily supply hours and power capacity for using medium/high-power appliances (e.g. TVs and refrigerators), are particularly relevant in the context of deprived rural areas of developing countries, but have not been fully studied so far.

From a methodological perspective, Choice Experiments and Contingent Valuation are the most applied methods in the literature to elicit households' WTP for electricity supply. Choice Experiments is particularly suitable for multi-attribute valuation because this method defines goods/services with multiple attributes and allows researchers to reveal respondents' preferences for each attribute and estimate the marginal WTP for changes in attribute levels (e.g. how much respondents are willing to pay for extending 1 h of daily electricity supply). The World Bank's MTF of energy access, which uses multiple attributes to define different tiers of electricity access, not only provides a policy-relevant rationale for selecting power quality attributes to design choice experiments, but also indicates a potential direction of how choice experiment results can be used by a wide range of stakeholders who use the MTF in their work to improve energy access around the world. However, to our best knowledge, barely any choice experiment studies have adopted or adapted the World Bank's MTF for designing the experiments or discussing the implications of the study results.

This study adapted the attributes of the World Bank's MTF of household electricity access and conducted a Choice Experiment survey in Sumba Island of Indonesia to investigate households' preferences and WTP for improving the quality of electricity supply in terms of four attributes: daily supply hours, frequency of unplanned power-cuts, diversity of usable appliances (indicating the peak capacity of using medium/high-power appliances), and monthly electricity fees. Sumba Island is a typical example of a deprived area in a developing country where the electrification rate has increased but the quality of electricity supply in many villages remains relatively low. The low-quality electricity supply has impeded the use of appliances that can improve life quality and support income-generating activities. A better understanding of households' preferences and WTP for better quality of electricity supply could provide helpful information for further efforts to improve energy access and achieve the SDG7 in Sumba and areas alike in the developing world.

The rest of this paper is arranged as follows. Section 2 provides a brief review of existing literature and highlights the major limitations. Section 3 explains research methods in terms of the study area, survey implementation, experiment design and theoretical models. Section 4 presents the research results, followed by discussions of policy implications in Section 5 and conclusions in the final section.

2. Literature review

The existing literature on households' WTP for electricity supply is largely directed towards WTP for green/renewable electricity [9–15,22–24], while a relatively small group of WTP studies have addressed the quality of electricity supply. For example, Carlsson and Martinsson [25] applied the choice experiment method to estimate Swedish households' WTP for reducing outages in terms of duration, time of the week, and time of the year. Pepermans [26] applied the same method to investigate how much compensation northern Belgian households required for different levels of outages in terms of frequency, duration, occurrence period (peak/off-peak time) & season (winter/summer), and advance notice. Similar choice experiment studies on households' WTP for the reliability of electricity supply have been conducted in Australia [27], northwest England [28], and on a larger scale across 19 European Union countries [18]. In developing countries, choice experiment studies have been carried out in India [29], Bangladesh [30], and Kenya [19,31] to understand households' WTP for reducing the frequency and duration of power-cuts, as well as their preference for the time of power-cuts, advance notification, and the type of power service providers. Only one choice experiment study has been conducted on consumers' WTP for electricity services in Indonesia, which targeted at urban residents and examined the attributes of rural electrification rate, duration of power-cut per year, and percentage of hydro-power in the energy source [32]. The authors found that, in the City of Bandung, households' WTP for reducing power-cut duration from 5 h to 2 h per year ranged between 5,000 Rp ($1.18) to 61,500 Rp ($14.49) per month. This WTP estimate for urban households has very limited implication to off-grid households in remote, rural areas of Indonesia who experience 2–5 h or even longer duration of power-cut almost every day.

Contingent Valuation has also been used to estimate households' WTP for improving the quality of electricity supply, but this method is only able to valuate specified scenarios of power supply as a whole, rather than examining multiple attributes of electricity services. For example, a contingent valuation survey in North Cyprus estimated households' WTP for having an inverter system to avoid power-cuts [33], while a study in northeast USA estimated residential customers' WTP for back-up electricity supply in a hypothetical event of 10-day black-out during cold winter [20]. In developing countries, Taale and Kyeremeh [16] investigated households' WTP for reliable electricity services in Ghana, but they did not specify the definition of “reliable service”. Similarly, Kunaifi and Reinders [34] investigated the perceived reliability of electricity supply in urban Indonesia and asked a simple question about WTP for “better electricity service”, but neither did them specify the definition of “better electricity service”. Several other studies had clearer specification of reliable/better electricity supply for valuation. A study in northern India estimated households' WTP for four additional hours of continuous electricity supply per day [35]. Another study in Ghana examined how trust in government could influence households' WTP for 24-hour electricity supply [36], so was 24/7 continuous power service valuated in Senegal [37]. As the only study that linked contingent valuation with the World Bank's MTF of electricity access, Sievert and Steinbuks [38] used grid electricity, a solar home system, and a solar lamp to roughly indicate different tiers of electricity access and estimated rural households' WTP for different types of electricity supply in Burkina Faso, Senegal, and Rwanda. Their results show that rural households in those three Sub-Saharan countries were willing to pay $4.5 to $14.3 per month for solar lamp (below Tier 1), $7.1 to $15.3 per month for solar home system (Tier 2 or 3), and $9.6 to $22.3 per month for grid access (Tier 3 or 4). Due to the limitation of the Contingent Valuation method, they did not estimate households' WTP for improvement in any specific attributes of electricity supply.

WTP studies for power service reliability can be linked to the literature on Customer Damage Function (CDF), which describes the relationship between customers' economic losses caused by interruption of power supply (also mentioned as interruption cost) and the interruption (power-cut) duration, along with other determinants regarding interruption attributes (e.g., season, time of the day, day of the week), customer characteristics, and environmental attributes (e.g., temperature, humidity) [39–41]. Survey-based WTP approach is one of the widely accepted methods of constructing CDF [42,43], which can be used for cost-benefit analysis of power resilience investment [44,45], optimal budget allocation [46], battery size optimisation of PV systems [47], and design of reliability insurance contracts [48].

Choice Experiment is believed to possess several advantages over traditional survey and Contingent Valuation methods [49,50]. First, it is easier to investigate people's WTP for individual attributes because of its way of describing the services/goods with multiple attributes at varied levels. Secondly, it could be more efficient to elicit people's true WTP by asking them to compare different options in multiple choice sets, instead of using direct and relatively simple WTP questions as other methods normally do. Lastly, it can collect more observations from the same number of respondents. On the downside, choice experiments usually take more efforts to design & implement and might cause confusion and impatience of respondents.

A major limitation of existing WTP studies on power supply quality is that they are mostly centred around attributes (or scenarios of electricity services) related to reliability (reduction of power-cuts), while other attributes that are particularly relevant to deprived rural areas of developing countries have not been fully studied. For example, the power capacity for using medium/high-power appliances (e.g. TVs, rice cookers, wash machines and refrigerators) is important for establishing micro-enterprises and improving household livelihood in low and middle-income countries, but has barely been addressed by previous WTP studies. Moreover, since 24-hour continuous power supply is not available in many rural areas of developing countries, the duration of daily electricity supply is probably a more suitable attribute to examine households' preferences for electricity supply in the developing world than the duration of power-cuts. Even for attributes related to power-cuts, it might be better to focus on unplanned power-cuts due to maintenance issues because intermittent power supply with "regular" power-cuts is the normality in areas without 24-hour power supply. These limitations of the existing literature underline the need for further empirical studies on households' preferences and WTP for quality of electricity access that focus on attributes highly relevant to the context of deprived areas of developing countries. This study aims to address those limitations and test the following hypotheses:

(a) Households' preferences for electricity services are significantly influenced by multiple power quality attributes: daily supply hours, frequency of unplanned power-cuts, diversity of usable appliances and monthly electricity fees.
(b) On-grid households and off-grid households have different preferences and WTP for improving power supply quality.
(c) There is significant heterogeneity in households' preferences for electricity services, which are associated with demographic characteristics (e.g., districts, gender, age, income).

3. Methods

3.1. Study area

Sumba is an island located in the eastern part of the Indonesian Archipelago, with a land area of 11,052 km^2 and a population of 779,049 in 2020. The average per capita income in Sumba is just about a quarter of the average national level, and the electrification rate of 24.5% in 2010 is far below the national level of 83.25% [51]. Since the implementation of the Sumba Iconic Island, a collaborative program between multiple domestic (e.g. the Ministry of Energy and Mineral Resources, the State Electricity Company and the local government) and international stakeholders (e.g. Hivos, the NGO introducing the program, and the Asian Development Bank), the electrification rate in Sumba more than doubled from 24.5% to 50.9% during 2011–2018 [52] and further increased to 74.2% in 2020 [53].

The main-grid of Sumba is mostly powered by diesel generators, while off-grid areas are mostly electrified by renewable energy. By 2018, the Sumba Iconic Island program had installed 68 small solar power stations with a total of 3.56 MW installed capacity, 17,840 home solar systems of 640 KW in total, 22 micro-hydro plants of 3.71 MW in total, as well as a 25 KW wind power plant [52]. Despite the increasing electrification rate, many households in Sumba still have intermittent, low quality of electricity supply for lighting bulbs and phone-charging only, making it difficult for them to make productive use of electricity and improve household livelihood. Information on households' WTP for better quality of electricity supply could help policy makers and other stakeholders to plan future investment and business models to further improve electricity access in Sumba.

The district level sociodemographic information of Sumba is presented in Table 1. East and Southwest Sumba Districts are more populous than Central and West Districts. East Sumba has both the highest electrification rate and income per capita among the four districts.

3.2. Survey implementation

Preparatory fieldwork of this study was conducted with a visit to four villages in Sumba to collect background information for the survey design. A pilot survey of 30 questionnaires was implemented to test the questionnaire. In March 2019, the main household survey was conducted by a team of staff from a local university. All interviews were conducted in the local language (Bahasa), and the enumerator team was trained by the research team before the main survey. A total of 400 questionnaires were collected from 18 villages across different administrative districts of Sumba (Fig. 1), and 399 valid questionnaires were used for data analysis. The number of valid questionnaires in each district was approximately proportional to the population of the district: i.e., 105 (26.3%) from East Sumba; 35 (8.7%) from Central Sumba; 67 (16.8%) from West Sumba; and 192 (48.1%) from Southwest Sumba.

The 18 villages were selected by consulting with local partners and stakeholders, including researchers of a local college, regional governmental officers, and local community leaders. Both research needs (representativeness) and practicality (accessibility of the villages) were considered as some remote, mountainous villages are very difficult to reach due to poor transport infrastructure. Interviewed households accounted for 10–20% of the selected villages. Households were randomly chosen in general, but the heads of villages were consulted to ensure that the survey covered households in diverse socioeconomic conditions.

3.3. Household characteristics

Descriptive statistics of sociodemographic characteristics of the sampled households are presented in Table 2. Most respondents (90.2%) were male since the survey was targeted at heads of households. 82.5% of respondents were between 31 and 60 years old and 40.6% of

Table 1
Sociodemographic information of Sumba Island.

Sociodemographic statistics	Sumba Island	East Sumba	Central Sumba	West Sumba	Southwest Sumba
Area (km^2) [51]	11,052	7,001	1,869	737	1,445
Number of households [54]	202,845	63,344 (31.2%)	17,815 (8.8%)	30,589 (15.1%)	91,097 (44.9%)
Electrification rate (2018) [52]	50.9%	76.1%	57.1%	43.5%	34.9%
Electrification rate (2020) [54]	74.2%	90.9%	73.0%	74.5%	62.8%
Income per capita (10^6 Rp/year) [51]	1.96	2.71	1.46	2.41	1.28

Rp: Indonesian Rupiah (14,000 Rp ≈ $1).

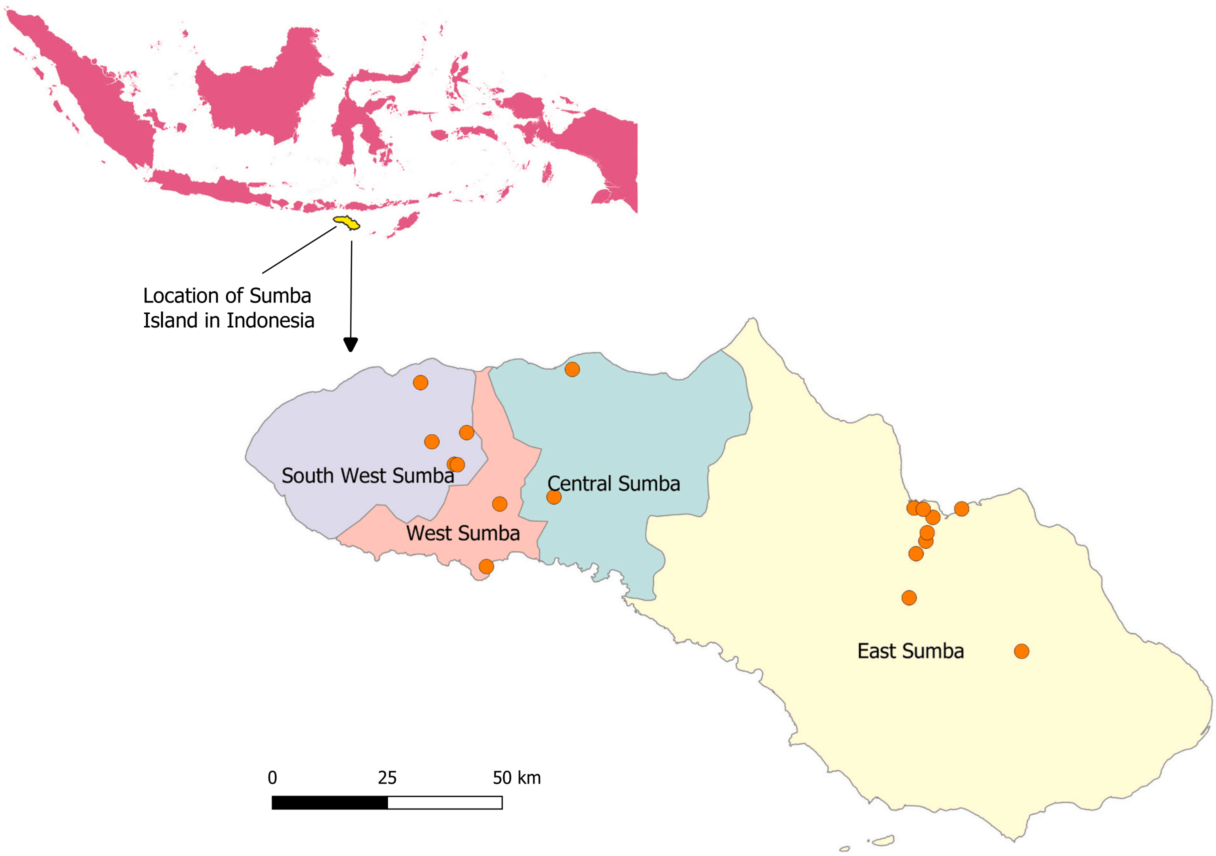

Fig. 1. Sampled villages in Sumba Island.
A total of 18 villages (points) were selected across four districts based on local informants' knowledge of the representativeness of villages at various socioeconomic status.

respondents only had primary or even less education. The median family size was five people per household. Based on the reported seven biggest income sources, the average annual household income of all households was 38.78 million Rp (about $2,770). Households of Central Sumba only had about half of the annual income of households in East Sumba and two thirds of income of households in West and Southwest Sumba. Main-grid (on-grid) households had more than double of the income of off-grid households (50.50 vs 22.07 million Rp).

Regarding the household use of appliances, most households had lighting bulbs (81.2%) and mobile phones (66.4%). Nearly 40% of households had a TV, around a quarter of them (24.8%) had rice cooker (s) at home, while only 15.5% owned a refrigerator. Nearly 60% of the households were connected to the main grid, while 18.5% had no electricity access in any forms at all. Over half (54.4%) of the main-grid users (households) were recently connected to the power grid in the last decade (2011–2019) after implementation of the Sumba Iconic Island program. About half of off-grid households had electricity access from alternative sources (e.g., mini-grids, home solar systems, accumulators), but very few of them used middle/high-power appliances at home. For example, only 6.1% of off-grid households had a TV while 61.1% of on-grid households did so.

Only households connected to the main-grid and mini-grids paid monthly electricity fees. On average, they paid 71,470 Rp ($5.11) per month for electricity, which accounted for 3.1% of their household income. East and Southwest Sumba households spent more on electricity (74,540 and 76,560 Rp/month) than those in Central and West Sumba (40,570 and 50,220 Rp/month). Electricity fees accounted for 1.4% (Central Sumba) - 3.5% (East Sumba) of household income across the four districts. On-grid households paid nearly three times as off-grid households paid for electricity (80,650 vs 27,350 Rp/month). Although very limited relevant data of Sumba Island or at the district level are available for comparison with the sampled households, our sample does provide a profile of households in a deprived region of a developing country with a recently improved electrification rate but relatively low quality of electricity supply.

3.4. Design of choice experiment

This study used four attributes to define the quality of electricity supply: daily supply hours, frequency of unplanned power-cuts, diversity of usable appliances, and monthly electricity fees. Selection of these attributes was based on the World Bank's MTF for measuring household electricity access [4] and the local context of Sumba as determined by information collected in the preparatory fieldwork and the pilot study. Different levels of the four attributes are described in Table 3.

The attribute of “diversity of usable appliances” indicates the peak power capacity for using various appliances. Generally, “low” level refers to using appliances below 50 W, “medium” for appliances between 50 W and 1000 W, and “high” for appliances above 1000 W. In practice, monthly electricity fees can be dependent on the quantity of power consumption. But this study adopted fixed tariffs instead of consumption-based tariffs as the monetary attribute, so monthly electricity fees here indicate the maximum WTP for electricity. In fact, fixed monthly electricity fees are quite common in Sumba, especially in villages supplied with electricity capable of powering a low or medium diversity of appliances. The four levels of monthly electricity fees in our choice experiment (30,000 Rp - 250,000 Rp) are within the range of the 1st quartile (22,000 Rp) and the maximum monthly electricity fees (525,000 Rp) of the sampled households in the survey (Table 2). When

Table 2
Descriptive statistics of household characteristics.

Descriptive statistics[a]	Full sample	East Sumba	Central Sumba	West Sumba	Southwest Sumba	On-grid (main-grid)	Off-grid
Sample size	399	105 (26.3%)	35 (8.7%)	67 (16.8%)	192 (48.1%)	234 (58.6%)	165 (41.4%)
Gender (male) (399)	90.2%	93.3%	88.6%	89.6%	89.1%	89.3%	91.5%
Age (399)							
18–40	36.1%	31.4%	37.1%	44.8%	35.4%	34.6%	38.2%
41–60	51.1%	56.2%	60%	47.8%	47.9%	50.9%	51.5%
Above 60	12.8%	12.4%	2.9%	7.5%	16.7%	14.5%	10.3%
Education (359)							
Primary school & below	40.6%	35.2%	40.0%	46.3%	41.7%	35%	48.5%
Middle school	17.0%	21.0%	5.7%	20.9%	15.6%	17.9%	15.8%
High school	22.8%	25.7%	28.6%	16.4%	22.4%	26.1%	18.2%
College & above	9.5%	16.2%	8.6%	3.0%	8.3%	15.0%	1.8%
No answer	10.0%	1.9%	17.1%	13.4%	12.0%	6.0%	15.8%
Family size (396)	5.5	5.4	5.5	5.2	5.6	5.7	5.3
Annual household income (10^6 Rp) (398)							
1st quartile	14.00	23.88	10.75	14.47	12.50	17.70	10.88
Mean	38.78	48.40	23.80	35.14	37.58	50.50	22.07
3rd quartile	45.48	60.00	32.55	42.25	44.66	59.90	27.30
Electrification rate[b] (399)	81.5%	94.3%	37.1%	76.1%	84.4%	100%	55.8%
Power supply[c] (399)							
Main-grid	58.6%	60.0%	17.1%	47.8%	69.3%	100%	0.0%
Mini-grid	5.5%	21.0%	0.0%	0.0%	0.0%	2.6%	9.7%
Home solar systems	9.5%	2.9%	11.4%	10.4%	12.5%	1.3%	21.2%
Accumulator	3.0%	1.9%	2.9%	3.0%	3.6%	0.0%	7.3%
Use of appliances (399)							
Lighting bulb	81.2%	93.3%	34.3%	77.6%	84.4%	100%	55.8%
Mobile phone	66.4%	85.7%	31.4%	58.2%	65.1%	84.2%	41.2%
TV	38.3%	50.5%	14.3%	22.4%	41.7%	61.1%	6.1%
Rice cooker	24.8%	31.4%	0.0%	9.0%	31.3%	40.6%	2.4%
Fridge	16.5%	21.9%	2.9%	9.0%	18.8%	27.4%	1.2%
Monthly electricity fees (10^3 Rp) (273)[d]							
1st quartile	22.00	20.00	22.50	21.50	25.00	23.00	20.00
Mean	71.47	74.54	40.57	50.22	76.56	80.65	27.35
3rd quartile	100.0	100.0	51.50	53.50	102.0	102.0	25.00
Maximum	525.0	525.0	103.0	400.0	500.0	525.0	100.0
% of household income[e]	3.1%	3.5%	1.4%	1.5%	3.3%	3.4%	1.4%
Main-grid connection year (228)							
1982–2000	19.3%	20.7%	0.0%	0.0%	24.6%		
2001–2010	26.3%	29.3%	28.6%	9.1%	29.2%		
2011–2019	54.4%	50.0%	71.4%	90.9%	46.2%		

[a] Numbers in parentheses show the variable specific sample size.
[b] Electrified households include all households with any types of power supply (main-grid, mini-grid, home solar system, etc.).
[c] Some households have multiple sources of power supply.
[d] Only households connected to main-grid or mini-grid paid monthly electricity fees.
[e] Electricity fees as the average percentage of household income, which applied only for household connected to the main-grid or mini-grids.

Table 3
Attribute levels of power supply quality.

Attribute	Attribute levels
Daily supply hours	6 h; 12 h; 24 h.
Unplanned power-cuts	No power-cut at all; once a week; twice a week.
Diversity of usable appliances	*Low*: lighting bulb and hand-phone charger. *Medium*: all appliances above plus TV, DVD, computer, laptop, rice cooker, dough mixer, blender and refrigerator. *High*: all appliances above plus wash machine, air conditioning, hair dryer, electrical kettle.
Monthly electricity fees	30,000 Rp[a]; 60,000 Rp; 120,000 Rp; 250,000 Rp

[a] Rp: Indonesian Rupiah (14,000 Rp ≈ $1).

converted to annual fees, the four payment levels range from 0.93% to 7.74% of the average annual household income of the full sample.

A total of 36 choice cards were generated using the orthogonal fractional factorial experiment design method [55,56]. As exemplified in Table 4, each choice card had three options, two options of electricity services defined by the four attributes at varied levels and an opt-out option of "None of them".

To avoid causing tiredness and boredom of respondents, which might reduce the reliability of their answers, the 36 choice cards were divided into three blocks so that each respondent just answered one block of 12 choice cards. In each village, the interviewed households were randomly assigned to one of the three blocks and the number of households in each block were approximately equal. The order of presenting the choice cards to each respondent were also randomized in the survey. Before presenting the choice cards to the respondents, a brief explanation and

Table 4
An example of choice cards.

Attribute	Option 1	Option 2	
Daily supply hours	6 h	12 h	None of them
Unplanned power-cuts	No power-cut at all	Once a week	
Diversity of usable appliances	Lighting bulbs and hand-phone chargers	Lighting bulbs and mobile phone chargers + TV, DVD, computers, laptop, rice cooker, dough mixer, blender and refrigerator	
Monthly electricity fees	30,000 Rp	60,000 Rp	
Pleas tick your preferred choice	☐	☐	☐

reminder (as follows) was given in case they did not understand the questions or overestimated their WTP:

> "*Please choose your preferred electricity service in each card. If you don't like any of the proposed electricity services, you can choose the option of "None of them". When you make decisions, please consider the options presented in one card only each time, i.e. please don't compare them with options in other cards. Moreover, please consider your household's total disposal income when making the choices. Spending more money on electricity means that you will have less money to spend on other goods and services.*"

3.5. Theoretical models

Choice Experiment methodology originated from the Characteristic Theory of Consumption [57] and Random Utility Theory [58,59]. It assumes that people derive utility (an ordinal measure of satisfaction) from characteristics (attributes) of goods/services and make their choices to maximize the derived utility. When a respondent is given a choice card C to choose the preferred alternative, the utility of alternative i is supposed to be composed of a deterministic, observable component V_i and a random, unobservable error component ε_i:

$$U_i = V_i + \varepsilon_i \tag{1}$$

When the respondent compares alternative i with alternative j in choice card C, alternative i will be chosen only if it generates greater utility than alternative j. Thus, the probability of choosing alternative i from choice card C is:

$$Pr(i|C) = Pr\left(V_i + \varepsilon_i > V_j + \varepsilon_j; i \neq j; \forall j \in C\right) \tag{2}$$

When the random error terms ε_i and ε_j are independently and identically distributed as the Gumbel distribution, the probability of choosing alternative i is:

$$Pr(i) = \frac{exp(\mu V_i)}{\sum_{j \in C} exp(\mu V_j)} \tag{3}$$

where μ is a scale parameter assumed to be 1, indicating constant error variance. The deterministic component V_i is usually assumed to be a linear function of the attributes vector X_i and the coefficients vector β, namely $V_i = \beta X_i$. Eq. (3) can be rewritten as:

$$Pr(i) = \frac{exp(\beta X_i)}{\sum_{j \in C} exp(\beta X_j)} \tag{4}$$

There are four attributes of power supply quality in this study, daily supply hours and monthly electricity fees are continuous variables while unplanned power-cuts and diversity of usable appliances 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 two binary dummy variables, which are coded as 1 if they apply to the alternatives, otherwise coded as 0. Therefore, in this study, the linear utility function component βX in Eq. (4) is:

$$\begin{aligned} \beta X = {} & \beta_0 \times ASC + \beta_1 \times Supply\_hours + \\ & \beta_2 \times Monthly\_electricity\_fees + \\ & \beta_3 \times Once\_a\_week\_power\_cut + \\ & \beta_4 \times Twice\_a\_week\_power\_cut + \\ & \beta_5 \times Medium\_appliance\_diversity + \\ & \beta_6 \times High\_appliance\_diversity \end{aligned} \tag{5}$$

where ASC is the Alternative Specific Constant, which is coded as 0 if respondents choose the opt-out option in the choice cards, otherwise coded as 1. Under the assumption of Independent of Irrelevant Alternatives (IIA), which means that the ratio of choice probability between two alternatives is not influenced by the introduction or removal of other alternatives, Eq. (4) is the Conditional Logit Model (CLM) and the coefficients (β_0 to β_6) of variables in Eq. (5) can be estimated by maximum likelihood estimation procedures [55,60]. Marginal WTP for non-monetary attributes, i.e. how much respondents are willing to pay for each unit change of the attributes, can be calculated as:

$$\text{Marginal WTP} = -\frac{\beta_{nm}}{\beta_m} \tag{6}$$

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).

Heterogeneity in respondents' preference is an important issue of Choice Experiment research. The Random Parameter Logit Model (RPL), also called as Mixed Logit Model, can release the IIA assumption of CLM and take account of the heterogeneity in respondents' preferences [61–64]. RPL allows coefficients to randomly vary among respondents and follow certain statistic distributions. The most widely used distribution is the normal distribution, which can be described by the mean and standard deviation.

Eq. (4) is the probability function of choosing alternative i when the coefficients vector β is assumed to be homogenous (constant) among all respondents. Adding the subscripts n and t to indicate respondent n and choice set t respectively, Eq. (4) can be rewritten as:

$$P_{nit} = \frac{exp(\beta X_{nit})}{\sum_{j \in C} exp(\beta X_{njt})} \tag{7}$$

The probability of respondent n's sequence of choices over all choice cards (S_n) is the product of the choice probabilities:

$$S_n = \prod_t P_{nit}(\beta) \tag{8}$$

In the RPL, coefficient β follows the distribution θ^* (assumed to be a normal distribution determined by its mean and standard deviation in this study). Denote the probability density of the coefficient as $f(\beta|\theta^*)$, the probability of the choice sequence S_n is the integral of Eq. (8) over all possible values of β weighted by its probability density:

$$P_n(\theta^*) = \int S_n f(\beta|\theta^*) d\beta \tag{9}$$

Eq. (9) does not have a closed form for calculation, but a simulated maximum likelihood estimation can be used to determine the coefficient distribution θ^* [61,63]. A relatively large number (e.g. 100) of values of β are randomly drawn from a given distribution θ, then the probability of respondent n's sequence of choices for all choice cards can be approximated by averaging all the simulated probabilities:

$$P_n'(\theta^*) = \frac{1}{R} \sum_{r=1}^{R} P_n\left(\beta^{r|\theta}\right) \tag{10}$$

where R is the number of draws, $\beta^{r|\theta}$ is the rth draw of β from the given distribution θ. The simulated log-likelihood of the choice sequences of all respondents is:

$$SLL(\theta) = \sum_n ln\left[P_n'(\theta)\right] \tag{11}$$

Substitute Eqs. (7), (8) and (10) into Eq. (11):

$$SLL(\theta) = \sum_n ln\left[\frac{1}{R} \sum_{r=1}^{R} \prod_t \frac{exp\left(\beta^{r|\theta} X_{nit}\right)}{\sum_{j \in C} exp\left(\beta^{r|\theta} X_{njt}\right)}\right] \tag{12}$$

Maximum Likelihood Estimation can be used to find the mean and standard deviation of the normal distribution θ^* that maximizes the $SLL(\theta)$ in Eq. (12). If the standard deviation is statistically significant, there is significant heterogeneity in respondents' preferences for the attribute. The statistical software R and the "mlogit" package were used to perform the simulation and maximum likelihood estimation procedures in this study [60,65].

Lastly, interaction terms between household demographic characteristics and the four power quality attributes were introduced in RPL to reveal the potential source of the heterogeneity in households' preferences for power quality attributes.

4. Research results

4.1. Households' preferences and marginal WTP for power quality attributes

Table 5 presents the results (estimated unstandardized coefficients and goodness of fit) of conditional logit models of the full sample, the on-grid (main-grid)/off-grid subsamples, and the four district subsamples. The estimated coefficients indicate what a unit change in numeric variables (daily supply hours and monthly electricity fees) or the presence of categorical variables (two levels of unplanned power-cuts and diversity of appliances) can cause to the utility that households can derive from the chosen electricity services. The significance levels and signs (positive or negative) of the coefficients indicate whether households significantly prefer or dislike the increase/presence of the power quality attributes (variables).

For the full sample of all households, coefficients of all variables are significant at least at the 0.01 levels. The coefficients of daily supply hours and diversity of appliances are positive, while the coefficients of power-cuts and monthly electricity fees are negative. The results indicate that Sumba households in general showed statistically significant preference for longer supply hours and greater diversity of usable appliances, while they showed significant aversion to increase in unplanned power-cuts and electricity fees (in other words, they preferred fewer power-cuts and lower fees). The sub-samples of on-grid and off-grid households showed similar preference for power quality attributes except that off-grid households did not show significant aversion to once a week unplanned power-cuts.

The major district difference in households' preferences for power quality attributes was found in the attitudes towards unplanned power-cuts (Table 5). Only East Sumba households showed significant aversion to both once a week and twice a week unplanned power-cuts. Central and West Sumba households were not significantly averse to neither level of power-cuts, while Southwest Sumba households only showed significant aversion to twice a week unplanned power-cuts.

Table 6 presents the marginal WTP for power quality attributes, which were calculated using the coefficient ratios of non-monetary variables to the monetary variable (i.e., monthly electricity fees). For the numeric variable of daily supply hours, marginal WTP means how much households are willing to pay for each extra hour of electricity supply within the range of 6 to 24 h (namely the range between the lowest and highest levels of this attribute in the experiment design). For categorical variables of unplanned power-cuts and diversity of usable appliances, marginal WTP means how much households would pay for changing the attributes from the base level (i.e. no power-cuts and low diversity of appliances, respectively) to other levels. On average, Sumba households were willing to pay 6,120 Rp/month for each extra hour of electricity supply. Therefore, they would pay 73,440 Rp/month for 12 additional daily supply hours (e.g. from half-day to full-day supply). The negative marginal WTP for unplanned power-cuts indicate that, compared to the base level of no unplanned power-cuts at all, once a week and twice a week unplanned power-cuts would decrease Sumba households' WTP for electricity supply by 15,220 Rp/month and 24,240 Rp/month, respectively (in other words, they were willing to pay that much for avoiding once a week and twice a week unplanned power-cuts, respectively). For improvement in the diversity of appliances from the low (base) level (capable of using lighting bulbs and phone chargers only) to medium level (capable of using medium-power appliances, e.g. TV, rice cooker and refrigerator) and high level (capable of using high-power appliances, e.g. wash machine and air conditioning), Sumba households would be willing to pay 50,560 Rp/month and 84,620 Rp/month, respectively. The estimated marginal WTP for extending power supply from half-day to full-day, avoiding twice a week unplanned power-cuts, and using high-power appliances equal to 103%, 33.9%, and 118% of the average monthly electricity fees currently paid by the sampled households, respectively. When converted to annual expenditure, the marginal WTP figures range between 0.75% - 2.62% of the average annual household income of the full sample.

Comparison between on-grid and off-grid households finds that on-grid households were more willing to pay for improving the quality of electricity supply (Table 6). For example, on-grid households would pay 7,480 Rp/month for each extra hour of electricity supply while off-grid households would only pay 4,480 Rp/month. The difference between the two estimates is highly significant as there is no overlap between their 95% confidence intervals (Fig. 2a).

Marginal WTP for power quality attributes further reveals district disparities in Sumba (Table 6). Overall, East Sumba households were willing to pay much more for improving the quality of electricity supply than households in other districts. For example, the marginal households' WTP for each extra hour of daily electricity supply in East Sumba (9,360 Rp/month) is more than twice as much as the households' WTP in Central (3,780 Rp/month) and West Sumba (3,860 Rp/month). The differences between East Sumba and other three districts are highly significant given the non-overlapping confidence intervals of the WTP estimates (Fig. 2a).

As for the reliability of electricity supply, only households in East Sumba were willing to pay for avoiding both once a week and twice a week unplanned power-cuts. But their WTP for the two levels of power-cuts were almost the same (62,200 Rp/month and 62,150 Rp/month, respectively), so were the confidence intervals of the two estimates (Fig. 2b). This result suggests that increase in unplanned power-cuts from once a week to twice a week is largely tolerable to East Sumba households. Among the other three districts, Southwest Sumba is the only district where households were willing to pay for avoiding unplanned power-cuts (for twice a week only), and the marginal WTP

Table 5
Results of conditional logit models.

Variables	Estimated coefficients (unstandardized)						
	Full sample	On-grid	Off-grid	East Sumba	Central Sumba	West Sumba	Southwest Sumba
Alternative specific constant (ASC)	−0.406***	−0.691***	−0.007	−0.788***	0.509°	−0.235	−0.396***
Daily supply hours	0.069***	0.077***	0.057***	0.065***	0.061***	0.061***	0.077***
Unplanned power-cut: once a week	−0.171**	−0.212**	−0.104	−0.434***	−0.267	−0.015	−0.061
Unplanned power-cut: twice a week	−0.272***	−0.310***	−0.219*	−0.434***	−0.329°	0.049	−0.279***
Diversity of appliances: medium	0.567***	0.578***	0.558***	0.715***	0.434*	0.528***	0.533***
Diversity of appliances: high	0.949***	0.937***	0.989***	1.185***	0.702***	0.832***	0.933***
Monthly electricity fees[a]	−0.011***	−0.010***	−0.013***	−0.007***	−0.016***	−0.016***	−0.012***
Goodness of fit							
McFadden's R^2	0.190	0.188	0.202	0.156	0.242	0.226	0.210
AIC	8537.6	5025.4	3487.1	2351.6	713.6	1382.0	4013.7

Statistically significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1.
[a] Unit of monthly electricity fees used in the models is 10^3 Rp/month.

Table 6
Marginal WTP for power quality attributes.

Variables	Full sample	On-grid	Off-grid	East Sumba	Central Sumba	West Sumba	Southwest Sumba
			Daily supply hours (10^3 Rp/month/h)				
Mean	6.12	7.48	4.48	9.36	3.78	3.86	6.27
2.5% quantile	5.50	6.58	3.68	7.37	2.41	2.78	5.46
97.5% quantile	6.78	8.47	5.34	11.87	5.33	5.02	7.17
			Unplanned power-cut: once a week (10^3 Rp/month)				
Mean	−15.22	−20.59		−62.20			
2.5% quantile	−25.33	−35.40	n.s.	−96.70	n.s.	n.s.	n.s.
97.5% quantile	−5.14	−6.25		−31.46			
			Unplanned power-cut: twice a week (10^3 Rp/month)				
Mean	−24.24	−30.10	−17.21	−62.15			−22.86
2.5% quantile	−34.35	−44.85	−30.93	−96.46	n.s.	n.s.	−36.38
97.5% quantile	−14.28	−16.11	−3.62	−31.52			−9.66
			Diversity of appliances: medium (10^3 Rp/month)				
Mean	50.56	56.18	43.91	102.40	26.81	33.60	43.69
2.5% quantile	40.12	41.37	29.85	69.55	2.62	14.97	30.17
97.5% quantile	60.91	71.85	58.02	139.28	51.59	53.08	57.70
			Diversity of appliances: high (10^3 Rp/month)				
Mean	84.62	91.02	77.80	169.65	43.43	52.91	76.42
2.5% quantile	73.62	75.30	63.17	131.59	18.81	33.72	62.18
97.5% quantile	96.14	108.41	93.25	217.06	70.15	73.69	91.98

n.s.: not significant.
The 2.5% and 97.5% quantile values compose the 95% confidence intervals of the WTP estimates.
Negative WTP for unplanned power-cuts means that households would pay the positive amount for avoiding that level of power-cuts.

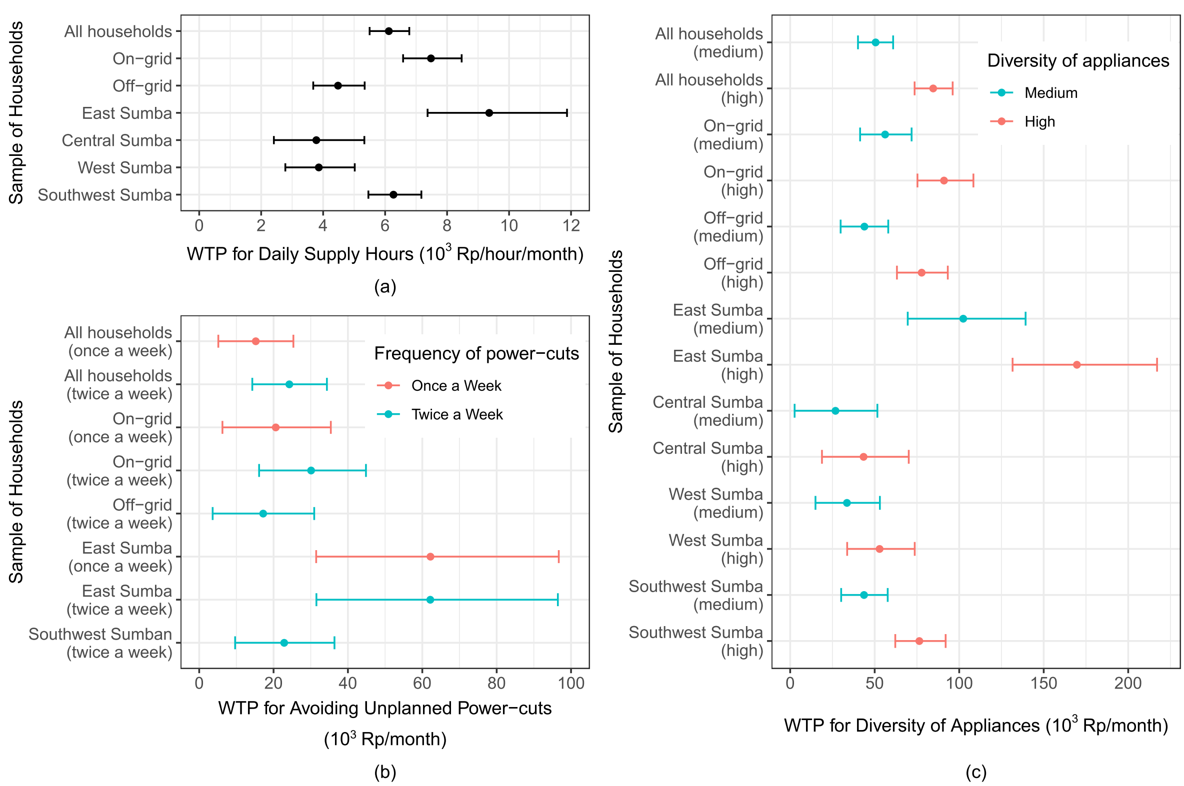

Fig. 2. Household marginal WTP for power quality attributes.
Points represent the estimated mean WTPs and lines represent the 95% confidence intervals. Negative marginal WTP for having unplanned power-cuts are converted to positive WTP for avoiding power-cuts, and sub-samples with no significant estimates are not plotted in sub-figure (b).

(22,860 Rp/month) was only around one third of that of East Sumba households.

Significant district disparities were also found in households' WTP for improving the diversity of usable appliances. East Sumba households would pay 102,400 Rp/month for using medium-power appliances and 169,650 Rp/month for using high-power appliances, which are nearly four times as much as Central Sumba households would pay (26,810 Rp/month and 43,430 Rp/month, respectively), more than three times as much as West Sumba households would pay (33,600 Rp/month and 52,910 Rp/month, respectively), and twice as much as Southwest Sumba households would pay (43,690 Rp/month and 76,420 Rp/month, respectively). As indicated by the confidence intervals of the

WTP estimates (Fig. 2c), the differences in households' WTP for appliance diversity were highly significant between East Sumba and the other three districts, while the differences between the other three districts themselves are less significant. Moreover, the differences in marginal WTP for the two levels of appliance diversity (medium vs. high) were more significant in East and Southwest Sumba.

4.2. Heterogeneity in households' preferences for power quality attributes

Table 7 presents the results of Random Parameter Logit (RPL) models (i.e. mixed logit model) that reveal the heterogeneity in households' preferences for power quality attributes. All attributes except unplanned power-cuts have significant standard deviation coefficients, which means that households' aversion to unplanned power-cuts is homogeneous, while their preference for the other attributes is significantly heterogeneous.

Multiple demographic and socioeconomic characteristics were introduced into the RPL model to form interaction terms with power quality attributes to help understand the heterogeneity in households' preferences (Table 7). Respondents' age, gender, education level and annual household income showed significant influence on their preference for power quality attributes. Respondents (heads of households) above 60 years old were found to have stronger preference for longer power supply duration. Households with higher annual income showed stronger aversion to unplanned power-cuts. Female respondents showed stronger preference for greater diversity of usable appliances than male respondents, especially for the power capacity of using medium-power appliances. Gender did not exhibit significant difference in terms of attitudes towards monthly electricity fees, neither did middle age (40–60) respondents differ from young respondents (18–40). But old respondents above 60 were more averse to the cost of electricity. Somehow, households with higher annual income were more sensitive to higher electricity fees, though the effect is rather slight. Lastly, respondents with higher education level were more tolerant of increase in monthly electricity fees.

Table 7
Heterogeneity in households' preferences for power quality attributes.

Variables	RPL[a]	RPL with interaction terms[b]
Mean coefficients		
Alternative specific constant	0.048	0.052
Daily supply hours	0.093***	0.095***
Unplanned power-cut: once a week	−0.265***	−0.114
Unplanned power-cut: twice a week	−0.351***	−0.290***
Diversity of appliances: medium	0.731***	0.661***
Diversity of appliances: high	1.089***	1.075***
Monthly electricity fees	−0.023***	−0.025***
Standard deviation coefficients		
Sd_Daily supply hours	0.070***	0.065***
Sd_Power-cut: once a week	0.099	0.062
Sd_Power-cut: twice a week	0.119	0.027
Sd_Diversity of appliances: medium	0.526***	0.529***
Sd_Diversity of appliances: high	0.535***	0.570***
Sd_Monthly electricity fees	0.016***	0.016***
Interaction with daily supply hours		
Age (41–60)		−0.007
Age (above 60)		0.042***
Interaction with unplanned power-cuts		
Annual income (once a week)		−0.004**
Annual income (twice a week)		−0.003*
Interaction with diversity of appliances		
Female (medium)		0.953***
Female (high)		0.810***
Interaction with monthly electricity fees		
Female		0.002
Age (41–60)		5.34E-06
Age (above 60)		−0.006***
Education		0.002***
Annual income (Rp 10^6)		−2.57E-05**
Goodness of fit		
McFadden's R^2	0.265	0.351
AIC	7749.39	6863.61

Statistically significance level: "***" 0.001, "**" 0.01, "*" 0.05, "°" 0.1.
[a] RPL: Random Parameter Logit Model (also called as Mixed Logit Model).
[b] Not all interaction terms between household characteristics and quality attributes of electricity supply were kept in the model. A stepwise-like selection procedure was conducted to remove interaction terms with least significance.

5. Discussion

5.1. Electricity service quality beyond reliability

Indonesia is an archipelago composed of more than 17,000 islands, of which about 6,000 are inhabited. There are thousands of islands that are too small and remote to feasibly equip with large-scale electricity supply infrastructure. Despite a considerable amount of pilot and implementation activities to improve rural electrification across Indonesia like the Sumba Iconic Island program, few socioeconomic studies have been published on the quality of electricity access in the country. The only comparable results from previous studies in Indonesia show that urban households in three cities were willing to pay \$3 to \$8 per month for improved reliability of electricity supply [34]. This result is higher than the average WTP of our full sample of households for avoiding twice a week unplanned power-cuts, 24,240 Rp (\$1.73) per month, but consistent with our result of the most well-off subsample of East Sumba households, 62,200 Rp (\$4.44) per month (Table 6).

As summarised in the Literature Review section, previous studies on WTP for power supply quality are mostly focused on reliability (reducing power-cuts). However, as we found in this study, multiple subsamples of Sumba households did not show significant preference for avoiding unplanned power-cuts. For those who did so, their marginal WTP for avoiding unplanned power-cuts was lower than the marginal WTP for extending daily supply for more than 8 h or improving the diversity of usable appliances. In other words, reliability of power supply is neither the most significant nor the most valued power quality attribute to Sumba households. The implication to researchers and policy makers is that efforts to improve the quality of electricity access in developing countries should consider not only reliability but also other attributes important to local households, such as daily supply hours and power capacity of using medium and high-power appliances.

Renewable energy is particularly important for remote, "isolated" areas like Sumba Island as the transport cost of fossil fuels is particularly high for them. To a wider extent, the results of this study have several policy implications for the penetration of renewable energy in Sumba and similar deprived areas in developing countries. First, households' demand and WTP for longer supply hours and greater diversity of usable appliances indicate that it could be promising to develop renewables-based micro/mini-grids that are more expensive than other off-grid energy solutions (e.g., home solar system) but more capable of providing better quality of electricity services. Secondly, when there are limited resources and technical challenges to improve multiple power quality attributes at the same time, it could be more efficient in welfare improvement to prioritise investment in increasing the peak power capacity over providing uninterrupted 24-hour power supply, given the preference information from our choice experiment. Lastly, reliability might not be the most preferred and valued electricity service attribute in deprived off-grid areas, but still in significant demand by households in general. Hybrid micro/mini-grids based on multiple renewable energy sources (e.g., solar plus biofuel) could be a potential solution, given the intermittent nature of renewable energy sources.

5.2. Implications of heterogeneity in households' preferences and WTP

This study found significant district disparity in households' WTP for improving the quality of electricity access (Fig. 2). Such district disparity in WTP could partly be attributed to the income disparity between different districts of Sumba, which is reflected both in the district statistics (Table 1) and the descriptive statistics of our sampled households (Table 2). The district disparities in household income and WTP suggest a need to consider district equality in future efforts to improve energy access in Sumba. Income disparity might also help explain why on-grid households in our study were willing to pay more for power supply quality than off-grid households. Such difference in on-grid/off-grid households' income and WTP for electricity service quality implies a positive dynamic between electricity access, household income and electricity demand as reported in previous literature [66].

Other findings on the heterogeneity in households' preferences for power quality attributes indicate potential linkages between SDG7 and other SDGs. For example, female respondents' significantly stronger preference for using medium and high-power appliances indicates that women could particularly benefit from improvement in the quality of electricity access. Appliances like rice-cookers and refrigerators could save women time and effort in housework and create the possibility of micro-enterprises; while TVs and computers could help them receive and process information and enjoy some entertainment. The potential impact of improved electricity access on gender empowerment supports the argument that there is a clear linkage between SDG7 and SDG5 (gender equality) [1]. Similarly, older respondents' stronger preference for longer power supply hours and aversion to higher electricity fees imply that efforts to achieve SDG7 should take account of SDG10 (reduced inequalities) regarding old people.

5.3. Applying choice experiments with the MTF

The World Bank's MTF for measuring energy access has been increasingly adopted or adapted to replace the traditional, binary measurement [67–72]. This study demonstrates how the Choice Experiment method can be used to extend the applicability of the MTF in research on energy access. Attributes used by the MTF can be adopted/adapted to design Choice Experiments for revealing respondents' preferences and WTP. Moreover, estimated marginal WTP for individual attributes can be aggregated to calculate households' WTP for upgrades between different tiers of electricity access. For example, Tier 1 in the MTF refers to household electricity service of 4–8 h per day for lighting and phone charging only, while Tier 3 refers to the service of 8–16 h per day for powering medium-watt appliances (there is little difference between the two tiers in other attributes). Assuming the difference between Tier 1 and Tier 3 is 4–12 additional hours of daily power supply plus improving the level of appliance diversity from “low” to “medium”. Using the average WTP of the full sample of Sumba households for the two power quality attributes (Table 6), it can be easily calculated that Sumba households, on average, were willing to pay 75,035 Rp ($5.36) to 123,979 Rp ($8.86) per month for upgrading electricity access from Tier 1 to Tier 3.

Such information of households' WTP for different tiers of electricity access could help policy makers, energy companies and international organizations to design service-based tariff structures and gain better understanding of the potential financial returns of different grid upgrade and extension plans. Service-based tariffs charge different levels of electricity tariffs (either in monthly fees or prices per kWh) for different tiers of electricity services. Many rural households in developing countries are served by scattered, small energy systems of different technologies at different costs. Regulation on flat-rate tariffs cannot reflect the different costs of providing power services at different quality levels, which have hindered private investment in rural electrification [73,74]. Service-based tariffs allows targeted pricing for different customer segments, which offers higher-cost options to customers who show low WTP for poor quality of power supply but are willing to pay more for better services, while keeping the low-cost options of basic power service for more deprived households. Cross-subsidies from the well-off customers to deprived ones could be included in service-based tariff to address social equality along with economic efficiency of rural electrification.

5.4. Limitations and future research

There are some limitations in this study. First, the subsamples of Central and West Sumba households are small because we had a moderate-size full sample and assigned the district subsamples according to the proportions of district population to the total population. The subsample of female respondents is also small because our survey targeted heads of households, and most households in Sumba are traditionally led by men. The limitation of small subsamples demands caveats to interpret the modelling results of those subsamples. More empirical studies are needed to further reveal the district disparities and gender implication of rural electrification in Sumba. The social equality issues can be explored in more details in the future.

Secondly, to balance the research needs and implementation practicality, we adapted and simplified the World Bank's MTF of energy access to design our choice experiment. Not all power quality attributes used by the MTF or studied in previous literature were considered in this research. For example, we did not use the legality attribute in the MTF or an attribute to specify whether power-cuts occurred in weekdays or weekends. Future efforts could be aimed for more comprehensive and in-depth research on power quality attributes.

Lastly, one possible application of the results from WTP studies on power supply reliability is to construct Customer Damage Function of power-cuts, which could be used for planning of energy systems (e.g., battery size optimization). This topic is beyond the scope of this study but could be a direction of future research. More broadly speaking, a potential direction for interdisciplinary research in the future is to integrate results of choice experiments with techno-economic assessment [75–77] and spatial analysis [78,79] to develop optimized multi-tier investment plans for providing multi-tier energy services in developing countries.

6. Conclusions

This research adapted the World Bank's MTF of energy access and conducted a choice experiment study on Sumba Island in Indonesia to estimate households' preferences and WTP for improving the quality of electricity access. We found that households connected to the main-grid were willing to pay more for better quality of power supply than off-grid households, and there were significant disparities in households' WTP between different districts of Sumba. The heterogeneity in households' preferences for power quality attributes was significantly associated with gender, age, education level of the heads of households and annual household income. The results of this study suggest that reliability (reduction of power-cuts), despite being the most studied attribute in previous literature, is not necessarily the most significant or valued power quality attribute in deprived, off-grid areas of developing countries. Our findings on households' preferences and heterogeneity provide useful information for prioritising investment in improving electricity access with limited resources. The influence of gender and age on households' preferences implies the linkages between SDG7 and other SDGs, though caveats are needed to interpret the gender implication due to a small subsample of female respondents.

This research contributes to a better understanding of household demand for improving energy access in areas like Sumba where electrification rates have increased but the electricity service qualities remain relatively low. We argue that the quality of energy access should be addressed from multiple dimensions beyond reliability. This demand-side study is well aligned with the wider efforts of addressing both supply-side and demand-side issues in energy research and policy-making. Methodologically, we suggest that Choice Experiments, integrated with the World Bank's MTF of energy access, is a promising tool for taking account of households' needs and preferences in future efforts to achieve SDG7. Although this study focused on household electricity supply, our methodology can be applied with the MTF for other types of energy access, such as household cooking and heating solutions. Our efforts to address the policy-relevant issue of electricity services quality and engage with the MTF of measuring energy access echo with the call for promoting novelty, rigor, and style in energy social science [80].

Declaration of competing interest

The authors declare that they have no known conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study is undertaken under the project of Creating Resilient Sustainable Microgrids through Hybrid Renewable Energy Systems (EP/R030243/1), funded by The Engineering and Physical Sciences Research Council of UK.

References

[1] UNDESA, Accelerating SDG 7 achievement: policy briefs in support of the first SDG 7 review at the UN High-Level Political Forum 2018. https://sustainabledevelopment.un.org/content/documents/18041SDG7_Policy_Brief.pdf, 2018.
[2] D. Chirambo, Towards the achievement of SDG 7 in sub-Saharan Africa: creating synergies between Power Africa, Sustainable Energy for All and climate finance in-order to achieve universal energy access before 2030, Renew. Sust. Energ. Rev. 94 (2018) 600–608.
[3] IEA, IRENA, UNSD, WB, WHO, Tracking SDG 7: The Energy Progress Report 2019, Washington DC, 2019.
[4] M. Bhatia, N. Angelou, Beyond Connections: Energy Access Redefined, ESMAP Technical Report 008/15, World Bank, Washington, DC, 2015.
[5] ESMAP, Multi-Tier Framework for Measuring Energy Access. https://www.esmap.org/node/55526#targetText=MTF%20redefines%20energy%20access%20from,for%20all%20required%20energy%20services%E2%80%9D, 2018 (Accessed 5th Sep. 2019).
[6] J. Knuckles, Business models for mini-grid electricity in base of the pyramid markets, Energy Sustain. Dev. 31 (2016) 67–82.
[7] M. Alam, S. Bhattacharyya, Are the off-grid customers ready to pay for electricity from the decentralized renewable hybrid mini-grids? A study of willingness to pay in rural Bangladesh, Energy 139 (2017) 433–446.
[8] S.C. Bhattacharyya, Mini-grids for the base of the pyramid market: a critical review, Energies 11 (4) (2018) 21.
[9] S. Sundt, K. Rehdanz, Consumers' willingness to pay for green electricity: a meta-analysis of the literature, Energy Econ. 51 (2015) 1–8.
[10] L.A.G. Oerlemans, K.Y. Chan, J. Volschenk, Willingness to pay for green electricity: a review of the contingent valuation literature and its sources of error, Renew. Sust. Energ. Rev. 66 (2016) 875–885.
[11] M.A. Andor, M. Frondel, S. Sommer, Equity and the willingness to pay for green electricity in Germany, Nat. Energy 3 (10) (2018) 876–881.
[12] R. Neumann, G. Mehlkop, Framing electricity plan choices to enhance green energy usage: a choice experiment with panel data from Germany, Energy Res. Soc. Sci. 70 (2020).
[13] L. Knapp, E. O'Shaughnessy, J. Heeter, S. Mills, J.M. DeCicco, Will consumers really pay for green electricity? Comparing stated and revealed preferences for residential programs in the United States, Energy Res. Soc. Sci. 65 (2020) 11.
[14] S. Klain, T. Satterfield, K.M.A. Chan, K. Lindberg, Octopus's garden under the blade: boosting biodiversity increases willingness to pay for offshore wind in the United States, Energy Res. Soc. Sci. 69 (2020).
[15] T. Balezentis, D. Streimikiene, I. Mikalauskas, Z.Y. Shen, Towards carbon free economy and electricity: the puzzle of energy costs, sustainability and security based on willingness to pay, Energy 214 (2021) 9.
[16] F. Taale, C. Kyeremeh, Households' willingness to pay for reliable electricity services in Ghana, Renew. Sust. Energ. Rev. 62 (2016) 280–288.
[17] M.O. Oseni, Self-generation and households' willingness to pay for reliable electricity service in Nigeria, Energy J. 38 (4) (2017) 165–194.
[18] J. Cohen, K. Moeltner, J. Reichl, M. Schmidthaler, Effect of global warming on willingness to pay for uninterrupted electricity supply in European nations, Nat. Energy 3 (1) (2018) 37–45.
[19] K.H. Zemo, H.T. Kassahun, S.B. Olsen, Determinants of willingness-to-pay for attributes of power outage - an empirical discrete choice experiment addressing implications for fuel switching in developing countries, Energy 174 (2019) 206–215.
[20] S. Baik, A.L. Davis, J.W. Park, S. Sirinterlikci, M.G. Morgan, Estimating what US residential customers are willing to pay for resilience to large electricity outages of long duration, Nat. Energy 5 (3) (2020) 250–258.
[21] F. Carlsson, M. Kataria, E. Lampi, P. Martinsson, Past and present outage costs? A follow-up study of households? Willingness to pay to avoid power outages, Resour. Energy Econ. 64 (2021) 12.
[22] T. Arega, T. Tadesse, Household willingness to pay for green electricity in urban and peri-urban Tigray, northern Ethiopia: determinants and welfare effects, Energy Policy 100 (2017) 292–300.
[23] Y. Zhou, H.B. Chen, S.D. Xu, L.B. Wu, How cognitive bias and information disclosure affect the willingness of urban residents to pay for green power? J. Clean. Prod. 189 (2018) 552–562.
[24] A. Kowalska-Pyzalska, Do consumers want to pay for green electricity? A case study from Poland, Sustainability 11 (5) (2019) 20.
[25] F. Carlsson, P. Martinsson, Does it matter when a power outage occurs? A choice experiment study on the willingness to pay to avoid power outages, Energy Econ. 30 (3) (2008) 1232–1245.
[26] G. Pepermans, The value of continuous power supply for Flemish households, Energy Policy 39 (12) (2011) 7853–7864.
[27] D.A. Hensher, N. Shore, K. Train, Willingness to pay for residential electricity supply quality and reliability, Appl. Energy 115 (2014) 280–292.
[28] K. Morrissey, A. Plater, M. Dean, The cost of electric power outages in the residential sector: a willingness to pay approach, Appl. Energy 212 (2018) 141–150.
[29] J. Sagebiel, K. Rommel, Preferences for electricity supply attributes in emerging megacities - policy implications from a discrete choice experiment of private households in Hyderabad, India, Energy Sustain. Dev. 21 (2014) 89–99.
[30] J. Breit, S. Komatsu, S. Kaneko, P.P. Ghosh, Evaluating households' preferences regarding reducing power outages in rural areas: cases in the Ganges Floodplain in Bangladesh, Environ. Dev. Sustain. 18 (1) (2016) 73–94.
[31] S. Abdullah, P. Mariel, Choice experiment study on the willingness to pay to improve electricity services, Energy Policy 38 (8) (2010) 4570–4581.
[32] M. Siyaranamual, M. Amalia, A. Yusuf, A. Alisjahbana, Consumers' willingness to pay for electricity service attributes: a discrete choice experiment in urban Indonesia, Energy Rep. 6 (2020) 562–571.
[33] A. Ozbafli, G.P. Jenkins, The willingness to pay by households for improved reliability of electricity service in North Cyprus, Energy Policy 87 (2015) 359–369.
[34] A. Kunaifi, Reinders, perceived and reported reliability of the electricity supply at three urban locations in Indonesia, Energies 11 (1) (2018) 27.
[35] B. Blankenship, J.C.Y. Wong, J. Urpelainen, Explaining willingness to pay for pricing reforms that improve electricity service in India, Energy Policy 128 (2019) 459–469.
[36] A. Amoah, D.A. Larbi, D. Offei, A. Panin, In gov we trust: the less we pay for improved electricity supply in Ghana, Energy Sustain. Soc. 7 (2017) 9.
[37] J.W. Deutschmann, A. Postepska, L. Sarr, Measuring willingness to pay for reliable electricity: evidence from Senegal, World Dev. 138 (2021) 16.
[38] M. Sievert, J. Steinbuks, Willingness to pay for electricity access in extreme poverty: evidence from sub-Saharan Africa, World Dev. 128 (2020).
[39] J.S. Michael, G.M. Matthew, A.S. Josh, Estimated Value of Service Reliability for Electric Utility Customers in the United States, 2010, p. 130.
[40] R. Billinton, G. Wacker, R.K. Subramaniam, Factors affecting the development of a residential customer damage function, IEEE Trans. Power Syst. 2 (1) (1987) 204–209.
[41] K. Kim, Y. Cho, Estimation of power outage costs in the industrial sector of South Korea, Energy Policy 101 (2017) 236–245.
[42] S.A. Beni, M. Haghifam, R. Hammamian, Estimation of customers damage function by questionnaire method, in: 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), 2013, pp. 1–4.
[43] M.S. Kim, B.S. Lee, H.S. Lee, S.H. Lee, J. Lee, W. Kim, Robust estimation of outage costs in South Korea using a machine learning technique: Bayesian Tobit quantile regression, Appl. Energy 278 (2020) 12.
[44] N. Uthathip, P. Bhasaputra, W. Pattaraprakorn, IEEE, Outage Cost Assessment for Investment-Benefit Model of Smart Grid in Thailand, International Conference on Cogeneration, Small Power Plants and District Energy (ICUE), Bangkok, Thailand, 2016.
[45] K. Anderson, X.K. Li, S. Dalvi, S. Ericson, C. Barrows, C. Murphy, E. Hotchkiss, Integrating the value of electricity resilience in energy planning and operations decisions, IEEE Syst. J. 15 (1) (2021) 204–214.
[46] S. Tragoonthai, S. Chaitusaney, IEEE, Optimal Budget Allocation for Preventive Maintenance of Distribution System Considering Customer Outage Cost and Reliability Indices, in: 2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Phuket, Thailand, 2017, pp. 600–603.
[47] M. Mehrabankhomartash, M. Rayati, A. Sheikhi, A.M. Ranjbar, Practical battery size optimization of a PV system by considering individual customer damage function, Renew. Sust. Energ. Rev. 67 (2017) 36–50.
[48] S.M. Abedi, M.R. Haghifam, CDF-based reliability insurance contracts considering free-riding, Int. J. Electr. Power Energy Syst. 53 (2013) 949–955.
[49] N. Hanley, R.E. Wright, V. Adamowicz, Using choice experiments to value the environment - design issues, current experience and future prospects, Environ. Resour. Econ. 11 (3–4) (1998) 413–428.
[50] N. Hanley, D. MacMillan, R.E. Wright, C. Bullock, I. Simpson, D. Parsisson, B. Crabtree, Contingent valuation versus choice experiments: estimating the benefits of environmentally sensitive areas in Scotland, J. Agric. Econ. 49 (1) (1998) 1–15.
[51] Winrock-International, Fuel Independent Renewable Energy "Iconic Island"-Preliminary Resource Assessment, Sumba Iconic Island Reports, 2010.
[52] Dagi-Consulting, Monitoring & Evaluation Sumba Iconic Island Program 2018 Final Report, 2018.

[53] Department of Energy and Mineral Resources, Province of East Nusa Tenggara, 2020.
[54] Department of Energy and Mineral Resources, Province of East Nusa Tenggara, 2020.
[55] H. Aizaki, Basic functions for supporting an implementation of choice experiments in R, J. Stat. Softw. 50 (CS2) (2012) 1–24.
[56] J.J. Louviere, D.A. Hensher, J.D. Swait, Stated Choice Methods: Analysis and Applications, Cambridge University Press, 2000.
[57] K.J. Lancaster, A new approach to consumer theory, J. Polit. Econ. 74 (1966) 132–157.
[58] D. McFadden, Conditional logit analysis of qualitative choice behaviour, in: P. Zarembka (Ed.), Frontiers in Econometrics, Academic Press, New York, 1974, pp. 105–142.
[59] J.J. Louviere, D.A. Hensher, J.D. Swait, W. Adamowicz, Stated Choice Methods: Analysis and Applications, Cambridge University Press, 2000.
[60] R-Core-Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2021.
[61] K.E. Train, Recreation demand models with taste differences over people, Land Econ. 74 (2) (1998) 230–239.
[62] N. Hanley, R.E. Wright, B. Alvarez-Farizo, Estimating the economic value of improvements in river ecology using choice experiments: an application to the water framework directive, J. Environ. Manag. 78 (2) (2006) 183–193.
[63] E. Ruto, G. Garrod, Investigating farmers' preferences for the design of agri-environment schemes: a choice experiment approach, J. Environ. Plan. Manag. 52 (5) (2009) 631–647.
[64] K.E. Train, Discrete Choice Methods With Simulation, 2 ed., Cambridge University Press, Cambridge, 2009.
[65] Y. Croissant, mlogit: Multinomial Logit Model, 2013.
[66] F. Riva, H. Ahlborg, E. Hartvigsson, S. Pachauri, E. Colombo, Electricity access and rural development: review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling, Energy Sustain. Dev. 43 (2018) 203–223.
[67] F.F. Nerini, R. Dargaville, M. Howells, M. Bazilian, Estimating the cost of energy access: the case of the village of Suro Craic in Timor Leste, Energy 79 (2015) 385–397.
[68] S. Groh, S. Pachauri, R. Narasimha, What are we measuring? An empirical analysis of household electricity access metrics in rural Bangladesh, Energy Sustain. Dev. 30 (2016) 21–31.
[69] N. Narayan, A. Chamseddine, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, M. Zeman, Exploring the boundaries of Solar Home Systems (SHS) for off-grid electrification: optimal SHS sizing for the multi-tier framework for household electricity access, Appl. Energy 240 (2019) 907–917.
[70] M. Ray, B. Chakraborty, Impact of evolving technology on collaborative energy access scaling, Renew. Sust. Energ. Rev. 110 (2019) 13–27.
[71] S. Pachauri, N.D. Rao, Advancing energy poverty measurement for SDG7, Progress Energy 2 (4) (2020), 043001.
[72] S. Pachauri, N.D. Rao, Advancing energy poverty measurement for SDG7, Progress Energy 2 (4) (2020).
[73] N.J. Williams, P. Jaramillo, J. Taneja, T.S. Ustun, Enabling private sector investment in microgrid-based rural electrification in developing countries: a review, Renew. Sust. Energ. Rev. 52 (2015) 1268–1281.
[74] MGP, State of the Global Mini-grids Market Report 2020, Mini-Grids Partnership, 2020.
[75] A. Chaurey, T.C. Kandpal, A techno-economic comparison of rural electrification based on solar home systems and PV microgrids, Energy Policy 38 (6) (2010) 3118–3129.
[76] S.C. Bhattacharyya, Mini-grid based electrification in Bangladesh: technical configuration and business analysis, Renew. Energy 75 (2015) 745–761.
[77] P. Blechinger, C. Cader, P. Bertheau, H. Huyskens, R. Seguin, C. Breyer, Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands, Energy Policy 98 (2016) 674–687.
[78] D. Mentis, M. Andersson, M. Howells, H. Rogner, S. Siyal, O. Broad, A. Korkovelos, M. Bazilian, The benefits of geospatial planning in energy access - a case study on Ethiopia, Appl. Geogr. 72 (2016) 1–13.
[79] N. Moksnes, A. Korkovelos, D. Mentis, M. Howells, Electrification pathways for Kenya-linking spatial electrification analysis and medium to long term energy planning, Environ. Res. Lett. 12 (9) (2017) 13.
[80] B.K. Sovacool, J. Axsen, S. Sorrell, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci. 45 (2018) 12–42.