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Understanding the path towards a clean energy transition and post-electrification patterns of rural households

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ABSTRACT

This paper presents an analysis of the path towards a clean energy transition in rural areas, from the time that households do not have electricity access from any source, to when they get access to the national electricity; considering the intermediate access to an off-grid renewable technology, as well as the post-electrification years. For this, field household-level data are collected through surveys and electricity consumption measurements in rural Kenya. Potential electricity access transitions were analyzed, in which the determinants of grid-electricity and solar home system (SHS) adoption were identified, finding that factors such as peer-pressure, good quality housing materials, and a male as household head will increase the probabilities to up to 45% for grid-electricity adoption. Increasing the electricity price and the unreliability of the electricity service will have a negative effect on these probabilities, reducing them at rates from 5 to 22%. Households that had access to a SHS before getting grid-electricity connection are likely to consume 9 kWh/month (equivalent to 142KSh/month) more than those that did not have access to it. Results also show that women as decision-makers have a key role in the energy transition, as female-headed households are keener to move to cleaner fuels at an early stage. The post-electrification consumption peak is likely to occur until the third year of connection, as households acquire more power-consuming appliances; however, this is greatly affected by the electricity grid unreliability. These findings intend to fill in the knowledge gap on understanding each step of the energy ladder in rural areas, which can potentially support the design of energy access interventions and policy strategies.

Introduction

Energy transition in rural areas

Rural households in developing countries meet their energy needs with a variety of fuels that need to be combusted, mostly happening under an unsafe environment and in an inefficient way (Heltberg, 2004; Howells et al., 2005). According to the WHO (2020), women and children are the most vulnerable to suffer from health issues due to their constant exposure to combustion of traditional fuels, also they dedicate most of their time to collect these fuels. For improving the quality of life in rural areas accelerating their energy transition, the United Nations Sustainable Development Goal 7 was listed as priority, aiming at achieving global access to clean, sustainable and affordable energy by 2030 (SEforALL, 2020), focusing not only on electrification but also to provide access to clean fuels for cooking. However, understanding the fuels consumption of rural households and its evolution towards reaching a clean energy transition is complex due to the high dependence on different socioeconomic, behavioral, and geographic factors, subject as well to national policies.

For describing energy transition in rural areas, the *energy ladder* metaphor is often used. This states that households will move forward to cleaner and modern fuels to meet their energy needs as their income increases; existing as well the possibility that they use a fuels mix from the upper and lower steps of the ladder (Heltberg, 2004; Howells et al., 2005; Louw et al., 2008; van der Kroon et al., 2013). Another alternative is the *energy leapfrogging* which consists of bypassing the conventional path of the energy ladder (i.e. moving from firewood to charcoal) and move faster to modern fuels, such as renewable energy technologies, which often is considered as a misconception due to its technological and social challenges in terms of adoption (Murphy, 2001). However, according to different studies in the literature, energy transition does not take place as anticipated for households that get electricity access, as they keep consuming conventional fuels – especially for cooking, balancing their fuels usage (Andadari et al., 2014; Heltberg, 2004; Howells et al., 2005; Louw et al., 2008; Rehman et al., 2010).

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In addition, reaching a clean energy transition becomes even more difficult when there is a significant gender gap in rural communities and female-headed households do not have the same opportunities for development and financial access; for these reasons, they are less likely to be considered in national electrification programs (UN, 2020). This gap originates from the privation of women's participation on different schemes in society that contribute to human development, such as access to education, to the employment market, and to overtake leadership positions (Chant, 2008; Medeiros & Costa, 2008; Munien & Ahmed, 2012). All these factors justify why rural female population are often categorized as the “poorest among the poor”, for example, in Kenya 52.6% of the population living below the poverty line of $1.9 per day are females (World Poverty Clock, 2020).

Effects of electricity access

Over the years, economic development has been attributed as an effect of electricity access mainly by finding correlations between national scale indicators, such as Gross Domestic Product (GDP) and electrification rates (Lee et al., 2020a,b). Taking this as reference, efforts have been undertaken by policymakers and international funding organizations to increase the national electrification rates in developing countries. However, recent studies have presented evidence that home electrification alone is not enough to improve the economic outcomes for rural households, especially applicable to the poorest citizens (Lee et al., 2020a,b). The results of the previous studies show inconsistency with others that have found evidence of socioeconomic improvements as a post-electrification effect, most of them highlighting an impact specifically on the probability of employment for females, which further increases the household income. For example, Dinkelman (2011) found a 9.5% increase in female employment in South Africa, Grogan & Sadanand (2013) found a 23% increase for Nicaragua, and Barron & Torero (2017) found that it can generate average profits for women of around $1000 per year in El Salvador. While these studies focus on grid-electrification, others analyze the impacts of off-grid solar home systems (SHS) and mini-grids on improving the quality of life of rural households. For example, in WRI (2016) it was found evidence from India and Nepal that off-grid systems reduce significantly the kerosene consumption – especially for households with access to a SHS, benefits children's education, and boosts income-generating activities. More recently, Opiyo (2020) found that SHS can stimulate the electricity consumption of rural households once they are provided with grid-electricity. Nevertheless, as discussed in Bayer et al. (2020) and Lee et al. (2020a,b), results vary based on the methods applied to evaluate the effects of rural electrification from study to study, and these may be lingering reverse causality from other external phenomena.

Electricity consumption patterns

Apart from the wide range of studies analyzing the impacts of rural electrification, those dedicated to measuring the post-electrification electricity consumption patterns over time are scarce in the literature, and the few that exist mainly focus on measuring the impact of specific electrification policies. For example, authors in Pereira et al. (2010) found that the electrification regulations in Brazil reduced the energy poverty in the country and induced an increasing trend of electricity consumption of recently grid-connected households monitored from 2000 to 2004. A similar consumption pattern was found in Diaz et al. (2010), monitoring different mini-grid locations in Argentina from 2001 to 2008 and analyzing the performance of the installed off-grid supply technologies.

In addition, the deployment of energy-use surveys are a common practice for electrification projects developers during the planning stage for estimating the amount of electricity that their potential customers will consume. However, there are studies in the literature analyzing the accuracy of survey-based electricity consumption estimations compared to measured load profiles data such as Blodgett et al. (2017) and Hartvigsson & Ahlgren (2018); highlighting the significant inaccuracy of energy-use surveys for predicting the actual electricity consumption not only for the aggregated daily amount, but also for computing load profiles. Among the error sources, Blodgett et al. (2017) identified the appliances inventory, as in the surveys people are asked to predict the number of appliances that they will acquire when they get electricity access, hence they are prone to provide under or over estimations. To identify this, the study included an audit analysis for comparing the appliances inventory before and after the mini-grids were installed. However, the decision of appliances acquisition and the electricity consumption patterns might be influenced by the stage of the energy transition in which households currently are, for example, households that currently have access to a SHS could own already certain appliances and their priorities may not be the same as the ones that do not have electricity access at all. Nevertheless, this aspect has not been addressed in these studies.

Study objectives and paper structure

While the appointed studies contribute significantly to this field, there is scarce knowledge about how the energy transition happens at a household-level. This would include mapping the evolution of consumption patterns from the time that households do not have electricity access at all, to when they have access to the national electricity grid, considering as well the intermediate access to an off-grid technology and the post- electrification years. This knowledge is required for understanding the effects of each step of the energy ladder on rural households' behavior, from the decision-making process of adopting an energy access technology (grid-electricity or SHS), to measuring the influence of having had access to a SHS before grid-electricity on their post-electrification consumption patterns.

This paper aims at filling this gap considering village and household-level attributes from field data collection in rural Kenya from 250 surveyed households and electricity consumption measurements from 10 households that have been recently connected to the grid. Maximum likelihood probit models are applied to evaluate the potential electricity access transitions that are more likely to occur in rural communities, identifying the determinants of grid-electricity and SHS adoption. A multiple linear regression model was implemented for determining the most influential factors of electricity consumption, in which the impact of having access to a SHS before getting grid-electricity connection on the consumption is quantified. The post-electrification patterns are analyzed by classifying households based on their connection years, accounting for the evolution in time of fuels consumption, appliances acquisition patterns, and load profiles measured from representative households. In addition, the influence of women as decision-makers on the path towards a clean energy transition and post-electrification effects is estimated.

First, this paper provides background information on the Kenyan rural electrification context, including as well the state of the SHS market and penetration in the rural population. Then the methods applied are described, including the village selection and the field study design. The results are presented in four sections; in the first one, the determinants of grid-electricity and SHS adoption are identified. The second section presents an analysis of the electricity consumption drivers. In the third section, patterns based on electricity access level and the gender effect are discussed, making a cross-sectional comparison between households that do not have access to electricity, those that have access only to a SHS, and those that have access to grid-electricity. In the fourth section, the post-electrification effects are further analyzed, integrating the measured load profiles data. Finally, a comprehensive discussion on the analysis and conclusions are presented.

The Kenyan context and regulatory measures

Electricity grid access in rural settlements is limited to the ones that are located along major roads or near cities; and in the cases when grid is available, only the wealthiest households can afford connections, while all the rest remain "under-grid" (Boamah, 2020; Lee et al., 2020a,b; Murphy, 2001). The grid coverage in Kenya has rapidly increased due to different government initiatives undertaken specially during the last years going from 16% in 2003 to 75% in 2018 (World Bank, 2020b). Kenya Power & Lighting Company (KPLC), as the monopoly national utility company, was in charge of implementing subsidized government's electrification plans with success, giving electricity access to more than 280 public secondary schools by 2003 (Lee et al., 2020a,b). However, the goal of connecting all public secondary schools in the country enhanced the creation of the Rural Electrification Authority (REA) in the Energy Act 2006 as an independent agency from KPLC and dedicated to accelerate rural electrification, specially connecting markets, schools and health centers in densely populated areas (REREC, 2020). With this strategy, 90% of the identified public facilities were electrified by 2014 (Lee et al., 2020a,b); however, the rural electrification rates were not increasing. In 2015, the government announced the *Last Mile Connectivity Project* (LMCP) with the intention of extending the low voltage networks to reach the households located within a radius of 600 m from the installed transformers in public facilities. This is an undergoing program primarily subsidized by the African Development Bank and the World Bank (LMCP, 2020). In 2018, the *Kenya National Electrification Strategy* (KNES) was launched in governmental partnership with the World Bank, along with the *Electricity Sector Investment Prospectus*. Both aiming at achieving universal access to electricity for all Kenyans by 2022, improving the design of electrification projects and facilitating the project investment for on-grid and off-grid solutions (World Bank, 2020a). Therefore, in order to include off-grid electrification efforts in the electrification plans, REA changed in the Energy Act 2019 to Rural Electrification and Renewable Energy Corporation (REREC) (REREC, 2020).

On the other hand, SHS are becoming popular globally as a potential solution to alleviate energy access. In 2017, more than 122 million people obtained access through off-grid solar systems (mostly through solar lamps), while the volume of sales of SHS increased 77% in 2018, as people demanded more power capacity (REN21, 2019). In Kenya, as the market grows fast, the prices of these systems decline (Murphy, 2001), and large distributors such as M-KOPA – a national company, are leading the market by providing SHS to more than 750,000 homes and businesses (MKOPA, 2020).

Data collection

For the objective of this research, the areas of work were delimited following two considerations. When determining patterns of energy consumption between households that are not yet connected to the national electricity grid and households that already are, the first consideration was to select villages in which both mentioned samples were found under the same environment. The second consideration was that households connected to the national electricity grid should have been provided access for no longer than 10 years. The latter consideration accounts for the evolution of energy consumption patterns and socioeconomic changes in time, and it was determined having as reference studies that reflect potential changes in patterns for households having more than five years of connection, such as Diaz et al. (2010). To meet these considerations, it was required to have access from KPLC to a list of 5320 transformers located in all 47 counties to be included during the first phase of the LMCP, which started its implementation in 2015. This list allowed identifying households that were connected recently to the national electricity grid, and it would allow defining households within the same village that are not yet connected, since their location is not reached within the 600 m radius from the transformer.

Table 1
Comparison of country-county level macroeconomic and demographic indicators based on 2019 Household National Census data (KNBS, 2019).

Indicator	Busia	Siaya	Kenya
Total population (people)	893,653	993,165	47,564,296
Rural (%)	87.3	91.4	68.8
Electricity access (% of rural population, 2019)[a]	26.1	19.7	26.3
GDP per capita (current USD, 2019)	1445.1	884.6	1508.4
Impact of agriculture on GCP[b] (%, 2019)	57.7	53.2	37.7

[a] Percentage of people that stated having electricity as their source of lighting.
[b] Gross County Product.

To reduce the scope of the field study, the region of Western Kenya was selected considering the population density, existing infrastructure and socioeconomic conditions of rural population in the country. Finally, the counties of Busia and Siaya were selected because they can be representative of rural Kenya accounting for demographic and socioeconomic conditions. The comparison of some indicators used as reference can be found in Table 1 below and Table 1 in the Appendix.

Support from a local team was obtained for selecting the villages. The team had extensive experience performing field studies in both counties, for which they provided insights of villages based on the samples needed in this study. The list of transformers location from LMCP was compared against a list of suggested villages, and after contacting relevant local authorities, 17 villages were selected. The village elders were interviewed to gather relevant information within the boundaries of the village. This information is presented in Table 2 in the Appendix. In addition, the villages with more than three schools tend to have more transformers installed. According to the village elders, most of the existing transformers were installed under the framework of LMCP.

Sampling design

A stratified sampling survey design was applied, meaning that the households within a village were segregated into those connected to the electricity grid and those that are not connected, and then households were selected on a randomly basis among each group. The total sample size of connected households was estimated considering the average population from this group per village with a confidence level of 90%, a margin of error of 5% and a standard deviation of 50%. For the total sample size of not connected households, the same considerations were used except for the margin of error, which was estimated as 7% due to the large population from this group found in each village. These parameters were computed for each sample group using Eqs. (1) and (2), where n_o is the sample size without considering the finite population correction factor, Z corresponds to the confidence level score obtained from the statistical standard-normal Z-score table, p is the standard deviation, e is the margin of error. In Eq. (2), n is the sample size considering the finite population correction factor and N is the population.

$$n_o = Z^2 p(1-p)/e^2 \tag{1}$$

$$n = n_o N/[n_o + (N-1)] \tag{2}$$

When arriving to a village, the village elder would guide the team to households from each group, the team then would select random households for the surveys, considering a distance from sample to sample of at least five households on average, depending on the household density. Grid-connected households selected for the measurements were also chosen on a randomly basis. The field data collection took place on November–December of 2019.

Household surveys

Two questionnaires were carefully designed for gathering detailed household-level data documenting the housing characteristics, demographics, energy sources, fuel usage, appliances ownership, time use, and transport assets. Due to previous experience working with national census data and finding anomalies in the household income responses that tend to bias the results, the household's socioeconomic condition is evaluated using characteristics such as housing materials, assets, occupation, education level and monthly expenses instead. According to USAID (2004), most of rural population do not know exactly their income, as there are many income earners from several sources that may vary seasonally. Also, because they try to hide or alter this information from the interviewers to make them appear poorer with the idea of receiving assistance or because they are fearful of taxation or robbery.

The first questionnaire was directed to households that are not yet connected to the national grid, and the second one to households that are already connected. The major difference between both questionnaires is that the second one contained questions regarding the consumption behavior and perceptions before and after getting access to electricity from the national grid. Both questionnaires were translated to Swahili to avoid miscommunication and information loss. These were deployed using Open Data Kit (ODK)[1] and were carried out in the form of interviews conducted by a team of bilingual enumerators. For further analysis in this paper, the samples from the group of households that are not connected to the national grid were divided into two sub-groups. The groups are those that have access to electricity through a solar home system (hereafter "SHS households") and those that do not have access to electricity at all (hereafter "NA households" for "No Access households"). The final number of samples is 250, the details per village and share among each sample group are presented in Table 3 in the Appendix. The resulting datasets from the household surveys were then combined with sub-county demographic and socioeconomic data from the Kenya Population and Housing Census for the year 2019 (KNBS, 2019). The processed data collected at a household-level are available in Dominguez et al. (2020).

Measurements

Measurements of the electricity consumption were taken at a household level in 10 of the interviewed households that were connected to the national grid. As measuring devices, wireless AC clamp current meters were used, which measure the alternating current (AC) True Mean Root Square (TMRS) at a single-phase. These devices were selected due to their simple installation as they are clamped around and electrical conductor from the meter box without needing for re-wiring; as well as because of their data recording capacity and battery life. As in Hartvigsson & Ahlgren (2018), to overcome with the limitation of measuring only a single-phase load, in the cases of three-phase loads, these were assumed to be balanced. Four devices were used for taking the measurements of multiple households simultaneously. These recorded the electrical current at every 30 s for one week – including weekends. The households' village and connection years are presented in Table 4 in the Appendix, in which the ID of household measured (HH ID) is included for future reference in this paper.

Methods

Determinants of adoption of energy access technologies based on different transitions

Since households included in the study were not followed-up in time, a cross-sectional analysis was carried out among sample groups. Maximum likelihood probit modeling was applied to identify the most significant attributes that are able to define the electricity access level of a household. This model allows the dependent variable to have two potential outcomes, estimating the probabilities for the independent variables of belonging to only one of them. In this case, the dependent variable is represented in a binary form either if a household belongs to the analyzed category (1) or not (0). Three models are proposed based on the potential household electricity access transitions that may occur in rural communities, and these transitions are assumed to be affected by different household and village-level conditions (Fig. 1).

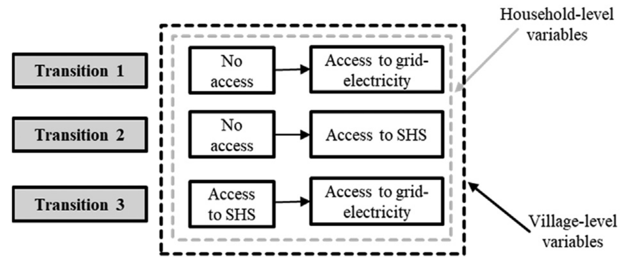

Fig. 1. Proposed household electricity access transitions and their drivers.

At a household-level, there were considered variables such as the household size, age and gender of household head, quality of housing materials, livestock ownership, access to clean cooking fuels, to education, etc. While at village-level, variables such as fuels prices, unreliability of the electricity grid, share of households with access to a SHS and to grid-electricity, etc. Further descriptions are found in Table 2. The village level variables were selected based on data availability on field. Among these, a binary variable was considered indicating whether the village has at least one transformer included in the LMCP or not, which can measure the impact that the LMCP may have on the adoption of grid-electricity or SHS. For the purpose of this analysis, it was assumed that all surveyed households in the LMCP villages have the possibility of being connected to the electricity grid, as most of them were located within the radius of 600 m from the transformers. Different fuels prices were also included, which were gathered from local markets/sellers in each village. The electricity price was estimated based on the households' monthly electricity consumption bill, accounting for the electricity tariff for 2018/19 for both categories of domestic consumers defined by KPLC based on the consumption units (kWh) per post-paid billing period or pre-paid purchased period.[2] The grid-electricity connection costs are constant for all the villages; therefore, it was not included in the models.

Furthermore, the transitions are described as follows, along with the datasets arrangements for formulating each model.

- Transition 1: households that have no access to electricity and get direct access to grid-electricity. For this model, data from NA households were taken along with data from Connected households that reported *not* having access to a SHS before getting access to grid-electricity.
- Transition 2: households that have no access to electricity and get access to a SHS. For this model, data from NA and SHS households were considered.
- Transition 3: households that have access to a SHS and get access to grid-electricity. For this model, data from SHS households together with data from Connected households that reported *having* access to a SHS before getting access to grid-electricity were used.

The models' notation is formally presented in Eq. (3), where P is the probability, A is the highest electricity access level for each category T (e.g. for transition 1 and 3 it would be getting access to grid-electricity connection, while for transition 2 is getting access to a SHS), φ is the

[1] ODK is an open-source offline data collection tool, available for download: https://getodk.org/.

[2] These categories are the "lifeline" (costumers that do not consume more than 10 units), paying 10KSh/kWh, and the "ordinary" (those that consume more than 10 units, but do not exceed 15,000), paying 15.8KSh/kWh.

Table 2
Results from the maximum likelihood probit models for identifying the electricity access level for each analyzed transition. The last column presents the results from the multiple linear regression model for estimating the electricity consumption.

	Electricity access level			Electricity consumption (kWh/month)
	Transition 1	Transition 2	Transition 3	(MLR)
Village level variables				
LMCP village	0.580	−0.107	0.647*	
	(0.437)	(0.444)	(0.335)	
Price of electricity (KSh/kWh)	−0.304**	−0.060	−0.124	−1.412
	(0.119)	(0.133)	(0.084)	(2.551)
Price of gas (KSh/refill)	−0.00005	−0.00001	0.0002	0.011
	(0.001)	(0.001)	(0.0005)	(0.018)
Price of charcoal (KSh/0.355 L)	0.001	0.001	−0.0004	−0.031
	(0.001)	(0.001)	(0.001)	(0.021)
Price of kerosene (KSh/0.5 L)	−0.008	−0.002	−0.003	−0.023
	(0.006)	(0.006)	(0.004)	(0.146)
Price of firewood (KSh/m^3)	0.002	0.001	0.001	−0.010
	(0.002)	(0.002)	(0.001)	(0.043)
Share of households with grid-access	2.743***	0.612	1.358**	
	(0.813)	(0.907)	(0.634)	
Share of households only with SHS-access	−0.283	0.501	−0.693	
	(0.998)	(1.192)	(0.808)	
Unreliability of supply	−0.981**	0.130	−0.819**	−8.849
	(0.411)	(0.498)	(0.326)	(11.772)
Household level variables				
SHS before connection				8.955
				(8.703)
Security lights ownership				5.877*
				(3.001)
Household size				2.245*
				(1.443)
Good quality walls[(a)]	1.256**	0.914	−0.428	−14.153
	(0.619)	(0.639)	(0.321)	(10.111)
Good quality floor[(b)]	1.034***	0.331	0.455	13.478
	(0.335)	(0.353)	(0.278)	(9.089)
Number of rooms	0.119	−0.034	0.138**	−0.217
	(0.078)	(0.085)	(0.057)	(1.855)
Access to clean cooking fuels[(c)]	4.987	1.726	0.054	27.011*
	(261.272)	(251.037)	(0.629)	(16.955)
Age of household head	0.004	−0.025***	0.019**	0.044
	(0.009)	(0.010)	(0.008)	(0.290)
Male as household head	1.189***	0.145	0.765***	−1.694
	(0.356)	(0.314)	(0.239)	(8.239)
Access to education[(d)]	0.348	1.133***	−0.146	3.953
	(0.497)	(0.413)	(0.264)	(8.458)
Agriculture as main occupation	−0.896*	0.058	−0.260	−1.782
	(0.485)	(0.528)	(0.302)	(10.122)
Home business other				0.477
				(34.728)
Home business selling				13.392
				(11.988)
Home business services using electricity				46.939**
				(20.415)
Home business services not using electricity				−1.081
				(10.800)
Small livestock ownership[(e)]	0.306***	0.022	0.031	0.449
	(0.091)	(0.094)	(0.053)	(1.783)
Poultry ownership	−0.063**	−0.024	−0.003	−0.733
	(0.026)	(0.023)	(0.013)	(0.564)
Large livestock ownership[(f)]	−0.085	0.113	−0.050	−1.491
	(0.095)	(0.103)	(0.058)	(2.280)
Small appliances ownership[(g)]	0.524**	0.354*	−0.123	0.910
	(0.206)	(0.185)	(0.096)	(2.969)
Large appliances ownership[(h)]	0.952***	0.142	0.434***	3.155
	(0.273)	(0.266)	(0.142)	(3.893)
Motorbikes ownership	0.758	0.852	−0.138	8.498
	(0.575)	(0.535)	(0.200)	(8.417)
Bicycles ownership	−0.047	0.070	−0.401*	4.337
	(0.322)	(0.306)	(0.207)	(6.269)
Constant	1.380	0.051	0.793	28.772
	(2.256)	(2.528)	(1.616)	(57.977)
Observations	198	126	190	90
R2				0.338
Residual Std. Error				29.570 (df = 61)
F Statistic				1.111 (df = 28; 61)
Log Likelihood	−56.572	−54.536	−87.520	
Akaike Inf. Crit.	163.145	159.071	225.04	

Note: the statistical significance is represented by $^{*}p < 0.1$;$^{**}p < 0.05$;$^{***}p < 0.01$, the robust standard errors are presented in parenthesis. [(a)] Walls made of brick or cement. [(b)] Floor made of concrete or ceramic tiles. [(c)] Access to clean fuels for cooking (Liquefied Petroleum Gas (LPG) and biogas). [(d)] Access to secondary and superior education. [(e)] Oxen, cattle. [(f)] Goats, pigs, sheep. [(g)] Electric and battery radio, mobile phone. [(h)] Television, DVD, refrigerator, sound equipment, sewing machine, portable computer.

cumulative distribution function based on the standard normal distribution, X represents a vector of household and village-level attributes and β is a vector of maximum likelihood parameters to be estimated.

$$P(A_T = 1|X) = \varphi(\beta X) \tag{3}$$

Drivers of electricity consumption

A Multiple Linear Regression (MLR) model was applied to identify the drivers for electricity consumption, considering different observed and measured household-level and village-level attributes. In addition, to estimate the impact of the transition path of electricity access on the households' electricity consumption, a binary variable is introduced to the model indicating whether the household had access to a SHS before getting connected to the electricity grid (1) or not (0). The unreliability of the electricity supply was measured implementing a binary variable that would identify if the household reported to have greater than or equal to six blackouts of more than 30 min last month (1) or not (0). The threshold amount of six blackouts was defined as it was the lowest amount reported in all the villages in the surveys. The electricity demand equation is formulated in Eq. (4).

$$E_{ij} = \alpha + \beta H_{ij} + \gamma V_j + \delta S_{ij} + \varepsilon_{ij} \tag{4}$$

where E_{ij} denotes the electricity consumption of household i in village j, H_{ij} is the vector of observed household-level attributes, V_j is a vector of observed village-level attributes, S_{ij} is the binary variable indicating the electricity transition path of the household. While ε_{ij} is the randomly distributed error, and α, β, γ, and δ are the least square parameters to be determined. It is important to note that while the MLR model is useful for determining the correlation among the studied variables and the electricity consumption, it does not consider the effects of causality embedded in the interaction among these variables at different levels, for which a more complex modeling approach might be required.

Results

Identifying the determinants for the adoption of solar home system technologies and grid-electricity

The first three columns of coefficients in Table 2 present the results for estimating the electricity access level for the three transitions analyzed in this study (Fig. 1). For transitions 1 and 3, the coefficients present the determinants for the adoption of grid-electricity for households that have no electricity access, and the ones that have access to a SHS, respectively, while for transition 2, the determinants of the adoption of SHS are identified. As the models implemented for this analysis are

Table 3
Marginal effects from the maximum likelihood probit models.

	Marginal effects: level of electricity access		
	Transition 1	Transition 2	Transition 3
Village level variables			
LMCP village	0.095	−0.026	0.172*
	(0.070)	(0.109)	(0.087)
Price of electricity (KSh/kWh)	−0.050**	−0.015	−0.033
	(0.019)	(0.032)	(0.022)
Share of households with grid-access	0.448***	0.150	0.362**
	(0.119)	(0.221)	(0.163)
Unreliability of supply	−0.160**	0.032	−0.218**
	(0.064)	(0.122)	(0.083)
Household level variables			
Good quality floor	0.169***	0.081	0.121
	(0.050)	(0.086)	(0.073)
Good quality walls	0.205**	0.224	−0.114
	(0.098)	(0.153)	(0.084)
Age of household head	0.001	−0.006***	0.005**
	(0.002)	(0.002)	(0.002)
Male as household head	0.194***	0.036	0.204***
	(0.053)	(0.077)	(0.059)
Small appliances ownership	0.086**	0.087*	−0.033
	(0.032)	(0.043)	(0.025)
Large appliances ownership	0.156***	0.035	0.116***
	(0.040)	(0.065)	(0.035)

Note: *p < 0.1; **p < 0.05; ***$p < 0.01$. Marginal effects at means are presented, robust standard errors in parenthesis.

non-linear, marginal effects are most appropriate to present the results rather than coefficients, as they show how the outcome variable will change when an independent variable changes (Blasch et al., 2019). Therefore, Table 3 presents the marginal effects of the most significant variables identified in Table 2.

From Tables 2 and 3 it can be observed that belonging to a LMCP village only has significant impact on transition 3, which means that it increases the probability by 17.2% that households that have a SHS adopt the grid-electricity. Interestingly, the price of electricity affects negatively not only transitions that involve grid-connection, but also transition 2 that considers the adoption of SHS. However, it is only statistically significant for transition 1, which means that one unit increase in the price of electricity will reduce the probability by 5% that NA households will adopt the grid-electricity. The share of households in the village that already have grid-electricity access was considered to account for the social pressure at a community scale, as specified in Khandker et al. (2014), peer pressure or demonstration effect tends to affect a household's electrification decision. This variable indeed shows a significant impact for transitions involving grid-connection, as increasing the share of grid-connected households in a village will increase the probability of grid-electricity adoption by 44.8% for NA households and by 36.2% for SHS households. The unreliability of the electricity supply also has a significant impact for both transitions 1 and 3, which means that by having an unreliable electricity supply in the village (at least six blackouts of more than 30 min per month), will reduce the probability of grid-electricity adoption by 16% for NA households and by 21.8% for SHS households. One of the reasons why the probability of adoption reduction for SHS households is larger than NA might be that they consider relying more on their current SHS than on the grid.

As for the household level variables, having good quality of floor and walls materials will increase the probability that NA households adopt the grid-electricity by 16.9% and 20.5%, respectively. As discussed in Household surveys section, the housing materials can be an observable indicator of the socioeconomic conditions of rural households, which would mean that they are able to afford the grid-connection and monthly consumption fees if they have good quality materials. The age of the household head has a significant impact on the adoption of SHS, as having a younger household head increases the probability by 99.4% that a household adopt a SHS, while for households that currently own a SHS, it will increase the probability of grid-electricity adoption to 99.5%. Having a male as a household head increases the probabilities of grid-electricity adoption by 19.4% for NA households, and 20.4 for SHS households, while it seems to reduce the adoption of SHS by 96% among samples. It can be observed that owning small appliances increases 9% of the probability of either adopting the grid-electricity or a SHS for NA households, while it reduces the probability by 3.3% of grid-electricity adoption for SHS households. The difference is seen for large appliances ownership, which increases the probabilities of grid-electricity adoption for both NA and SHS households by 15.5% and 11.6% respectively.

Electricity consumption: drivers and influence of electricity access transition path

The last column in Table 2 presents the estimates of the MLR model including the variables that are considered to affect the households' monthly electricity consumption. Interestingly, none of the village-level variables is statistically significant; however, the price of electricity and other fuels, as well as the unreliability of the electricity supply have a negative impact on the monthly consumption, except for the gas price, which presents having a positive correlation. From the most significant household level variables, it can be observed that the increase of one security light (lightbulbs for exterior lighting) ownership increases six times the electricity consumption. The increase of one household member will lead to an increase of consumption of 2.2 times, while having access to clean cooking fuels will increase the consumption by 27 kWh/month. To determine the impact of the electricity access transition on the electricity consumption, a binary variable indicating whether the household had access to a SHS before getting connected to the grid was implemented, introducing transitions 1 and 3 into the equation. While the variable does not seem to be statistically significant, it does have a positive impact on the outcome, which means that having access to a SHS before getting access to grid-electricity, increases the electricity consumption by 9 kWh/month among the samples, equivalent to 142KSh/month, considering the domestic 'ordinary' domestic tariff category of KPLC.

Patterns based on electricity access level and the gender effect

Electric devices ownership

For a better analysis, data of appliances ownership from the three sample groups of households (NA, SHS, and Connected) were classified based on the gender of the household head to identify patterns of ownership, which results are presented in Fig. 2 including the most popular appliances mentioned by the respondents. Interestingly, as a general trend, female-headed households (especially the ones having access to a SHS) own more variety of appliances than male-headed. Lightbulbs are the most popular electric device for female-headed households with an average of 3.4 and 2.5 devices for Connected and SHS households, respectively; for male-headed, lightbulbs are also the most popular (mainly among Connected households), with an average of 2.5 devices, followed closely by mobile phones with 2.5 devices. All households included in this study reported to own at least one mobile phone, including NA households.

In more than 50% of the cases, the household head makes the decision of which appliances to buy except for the SHS households, which 53% reported that the spouse is who decides; thus, according to Table 5 in the Appendix, this decision is taken mostly by males. Most households reported that they acquire their appliances in markets from a near town, except for SHS households, which mostly acquire them from a local provider. The most popular distributors of SHS in the studied areas are M-KOPA and SunKing, among their products there are sets including electric radios, televisions, lightbulbs, and a battery with USB ports for mobile phone charging; therefore, it is very likely that the appliances came together with their solar home systems.

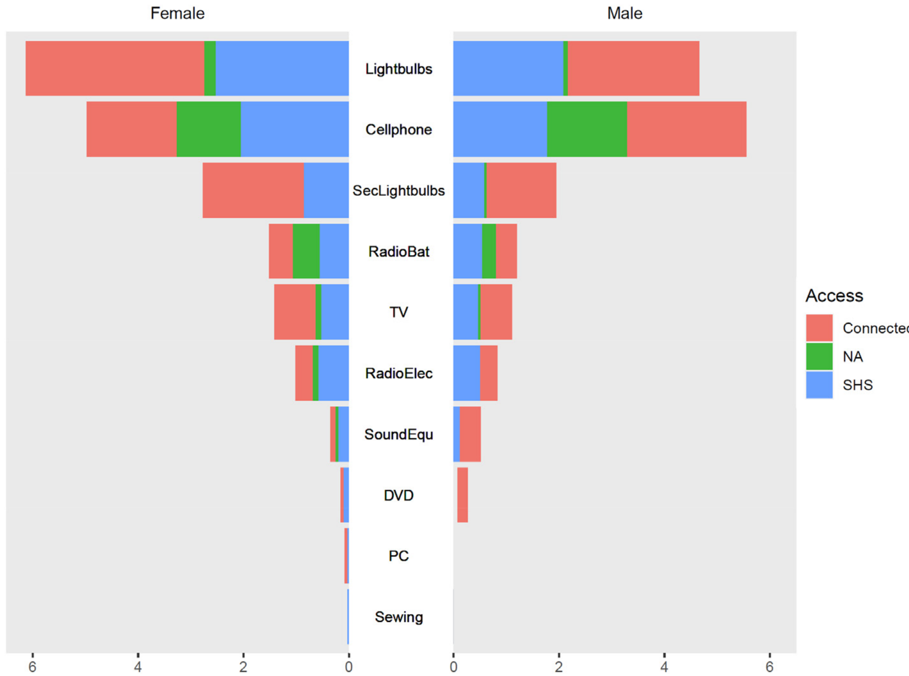

Fig. 2. Comparison of average appliances ownership between sample groups and female and male-headed households.

Meeting their entertainment needs is the reason why 79% of Connected households buy appliances, followed by increasing their productivity. Similarly, 75% of SHS households reported that entertainment is their main reason, followed by improving their children's education. On the other hand, for 50% of NA households, the main reason is to facilitate communication and to have access to information. These results give insights on how their priorities change based on their electricity access level, suggesting that rural households expand their horizons of opportunities for development as they move towards electrification. Discussions in the literature point out that the main use of electricity among rural households is for meeting their lighting needs (Dominguez et al., 2019), and Table 2 presents evidence of the specific influence of security lights ownership on the final electricity consumption; therefore, the power rates of lightbulbs and security lights were also documented. As expected, connected households own the highest power rates with a mean value of 31.64 W for lightbulbs and 28 W for security lights. With a vast difference, SHS households own lightbulbs of 5.27 W and security lights of 6.17 W. This power rates gap is attributed to the limited capacity that solar home systems usually offer.

Fuels consumption

Table 7 in the Appendix lists the average prices of each fuel; these were obtained from local markets in the studied villages. In Table 4, the average monthly fuels expenses for each sampling group based on their electricity access level are presented. To analyze the influence of having access to SHS before grid-electricity connection on other fuels consumption, Connected households were classified into the ones that did not have access to one before getting grid-electricity (Connected w/o SHS), and the ones that did (Connected w/SHS). On average, NA households spend more on kerosene and charcoal, while SHS and Connected households on gas and charcoal. It is important to mention that while NA households rely mostly on firewood for cooking, they do not spend much on it since it is collected by themselves. Interestingly, households that had access to a SHS before grid-electricity connection consume 5.1% more gas, 79% less kerosene, 4% more charcoal, and 43.5% less firewood than those households that had not access to it. This highlights the positive impacts of the integration of off-grid renewable energy technologies as a transitional step in the energy ladder.

Table 4
Mean monthly fuels expenditure by electricity access level, KSh/month, and changes in consumption based on analyzed transitions.

	Gas	Kerosene	Charcoal	Firewood
NA	40.00	170.50	124.17	70.00
SHS	203.03	119.24	260.15	90.98
Connected w/o SHS	208.97	88.72	199.76	86.27
Connected w/SHS	219.57	18.65	207.65	48.76
Changes in analyzed transitions				
Transition				
1	422.4%	−48.0%	60.9%	23.2%
2	407.6%	−30.1%	109.5%	30.0%
3	8.1%	−84.4%	−20.2%	−46.4%

Table 4 presents as well the changes of monthly fuels expenses between the three analyzed transitions. It can be observed that the gas expenditure of households is substantially greater when they move from NA to SHS (407.6%) than when they move from SHS to grid-electricity (8.1%). However, the most significant changes between households that move from SHS to grid-electricity can be identified in their reduction of kerosene, charcoal, and firewood consumption.

For further analysis, in Fig. 3 the influence of the household head gender on the average monthly fuel expenses are presented for the main sample groups. It is important to mention that connected households use kerosene as backup systems when electricity from the grid is not available. It is interesting to note that female-headed households from the NA and SHS groups rely more on kerosene than male-headed households, however, when they get access to grid-electricity, they consume less this fuel than male-headed. One of the most important gender effects to highlight is that female-headed households are the largest consumers of gas for cooking before and after electrification – with a reduced consumption of firewood, while male-headed tend to use more charcoal than gas for this purpose. Even more interesting, is that the gender difference among household heads is almost not significant for the electricity consumption, although female-headed households in this study presented to consume 1.3% more than male-headed.

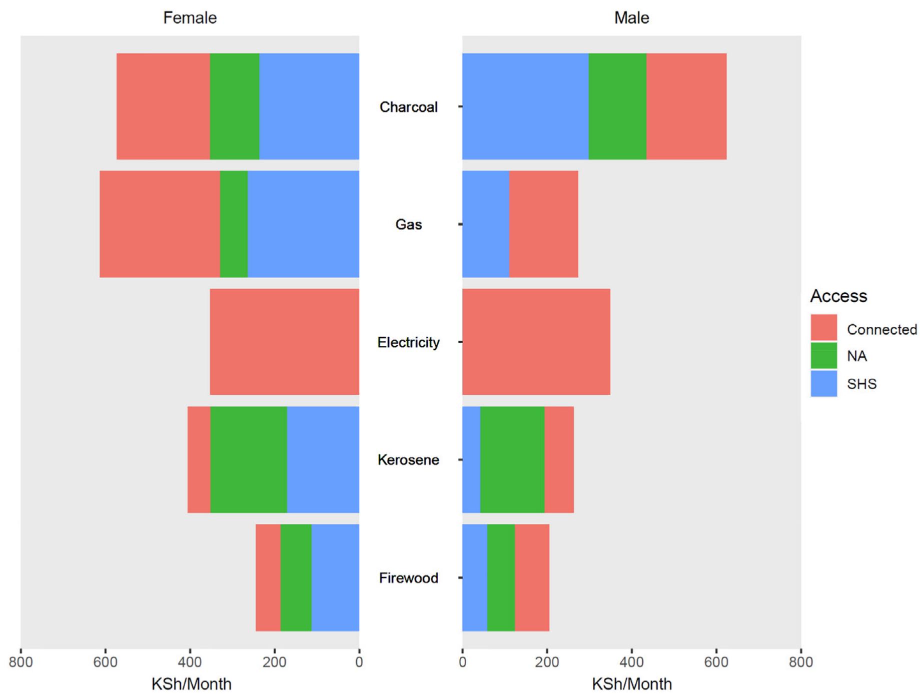

Fig. 3. Effect of household head gender on mean monthly fuel expenses among sample groups.

Post-electrification patterns

For further analysis, the households are grouped based on their distribution of connection time. The detailed socioeconomic characteristics of each connection-time group are presented in Table 6 in the Appendix.

Acquisition patterns of electric devices

From Fig. 4 (left) it is observed that households from around the second connection year on have more access to power-consuming appliances such as electric iron, hairdryer, and other equipment for productive use (e.g. woodcutters or agriculture machinery). In addition to electrical appliances, Fig. 4 (right) suggests that once households get electricity access they tend to buy more lightbulbs and security lights over the years; however, with the years they tend to reduce the power rates of their lightbulbs. This reduction might be attributed to their continued acquisition of appliances, which leads them to a significant increase in their electricity consumption (an increase in their expenses) consequently they try to regulate it by acquiring more efficient lightbulb devices. It is suggested that one of the reasons of the slight increase of their security lights' power rates can be triggered by their increasing need for security, now that they possess more electrical devices. Owning more electrical appliances, lightbulbs, and security lights affects directly the reliability of their electricity supply; this is represented by households' responses on their rates of dissatisfaction with their electricity supply (further explained in Fig. 6).

When project developers want to estimate the electricity that their future customers will consume, they often travel to specific sites and collect data through surveys; however, studies such as Blodgett et al. (2017), Hartvigsson & Ahlgren (2018) and Williams et al. (2018), argue that this technique tends to result in inaccurate estimations. Some of the reasons for this inaccuracy is that rural households are requested to mention the appliances they wish to acquire after they get access to electricity. Therefore, they picture a future scenario that can largely be influenced by their high desire of having a service that they do not currently have. In this study, Connected households were asked to mention the appliances they actually *acquired* as first priority during their first year of connection. Households that have less than one year of connection were asked for the appliances they already acquired and that are willing to acquire in the next months. To identify the influence on the appliances acquisition of the household head gender and the effect of having access to a SHS before grid-electricity connection, results are presented in Fig. 5.

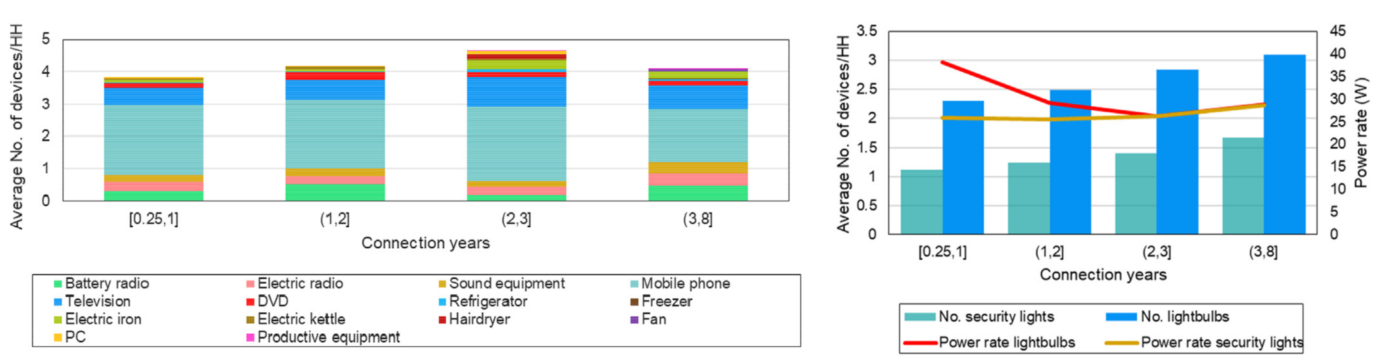

Fig. 4. Left, average appliances ownership by groups of connection years. Right, lightbulbs and security lights ownership and power rates by groups of connection years.

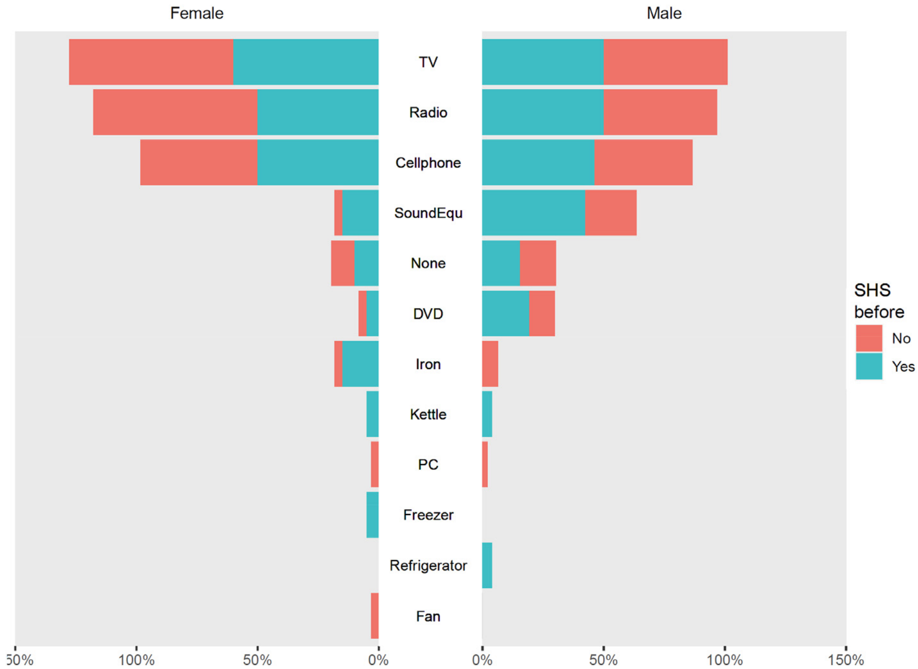

Fig. 5. First priority appliances for connected households, results presented by gender of the household head and having or not having access to a SHS before getting grid-connection.

For both female and male-headed households, televisions, radios, and cellphones are the most popular appliances acquired during the first connection year. Moreover, the influence of having access to a SHS before on the acquisition of these appliances is not evident. On the other hand, the acquisition of more power consuming appliances such as sound equipment, DVD, electric iron (especially for female-headed households), electric kettle, freezer, and refrigerator is indeed influenced on whether households had access to a SHS before getting grid-electricity connection.

Reliability of electricity supply as an influencing factor in the post-electrification behavior

Rural areas are characterized by being isolated settlements where most of the times their geographic location makes it difficult for being provided with proper basic infrastructure. Electricity supply is not an exception; once these areas are connected to the national grid, the reliability of the electricity supply becomes a problem. This may have as consequence that households do not rely entirely on the electricity grid to meet their needs, thus they need to use other fuels as backup systems (Khandker et al., 2014; Lee et al., 2020a,b). Fig. 6 shows the frequency of blackouts for more than 30 min in one month, as well as the percentage of households classifying their supply as irregular for each group of connection years. In addition, households were asked to qualitatively classify whether their electricity supply is regular or irregular; for which in all villages, more than 60% said it was irregular, showing a high dissatisfaction rate overall (Fig. 6). Households that have been recently connected and those around the third connection year report on having an average of more than eight blackouts of more than 30 min per month, while households from around the third year report the largest rate of dissatisfaction with their electricity supply service.

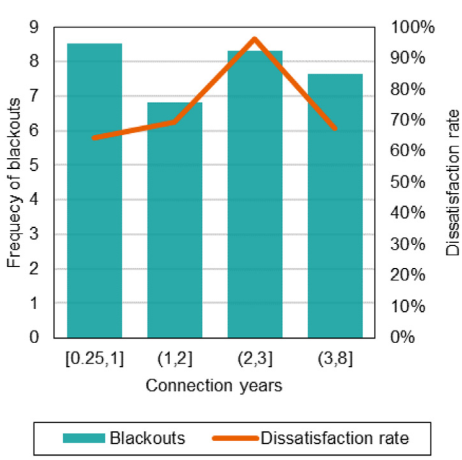

Fig. 6. Reliability of electricity supply, frequency of blackouts of more than 30 min per month and dissatisfaction rates among the sampled population.

Fuels usage over time

Table 5 presents the current monthly expenditure of the most commonly used fuels for each group of connection years, as well as their progressive changes in time. The most significant change in all fuels consumption is noted between the second and third year, especially in the increase of charcoal and their reduction of firewood expenditure. Concerning their electricity expenditure, there is no significant change after the third year of connection. This suggests that the electricity consumption peak may happen around the third year.

Table 5
Mean monthly fuels expenditure by group of connection years, KSh/month, and progressive changes in consumption.

Connection years	Electricity	Gas	Kerosene	Charcoal	Firewood
[0.25,1]	309.6	129.8	50.2	242.3	91.6
(1,2]	318.9	196.1	55.3	162.9	84.2
(2,3]	421.4	221.4	75	222.2	32.1
(3,8]	433.8	390	90.8	88.1	40.8
Changes in connection years					
[0.25,2]	+3.0%	+51.1%	+10.1%	−32.8%	−8.1%
(2,3]	+32.1%	+12.9%	+35.7%	+36.4%	−61.8%
(3,8]	+2.9%	+76.1%	+21.1%	−60.3%	+27.1%
Average	+12.7%	+46.7%	+22.3%	−18.9%	−14.3%

Load profiles measurements

Measurements of electricity consumption were taken from some of the households connected to the electricity grid. For consistency, these load profiles were grouped based on the connection years, the measurements for each group are found in Figs. 1–4 in the Appendix. From these load profiles, it is interesting to observe how the load shape changes with the years, starting from a reduced but constant consumption, which happens mostly during night and early morning hours (for the first connection year) to very intermittent an shifting consumption patterns through the day (after the third connection year). To determine the peak power consumption of each group of connection years and their frequency, load duration curves were computed aggregating all the measured days. In Fig. 7, the load duration curves for the first and second group of connection years are presented, the curves for the rest of group of connection years can be found in Figs. 5–6 in the Appendix. From Fig. 7, it is noticed that the electricity consumption from households that have been recently connected is mostly attributed to the use of lighting and security lights considering the hours and amount of consumption, having the peak power frequently at around 20:00 and 21:00 h. For households in their second connection year, the peak power seems to have more duration happening mostly around 19:00 and 21:00, a large load duration is also identified during the day hours representing the use of other appliances, mostly at 11:00, 14:00 and 15:00. It is interesting to see that the peak power of households in their first connection year is larger than the ones from the second year, this may be attributed to the fact that households from this group own more power-consuming lightbulbs and security lights (Fig. 4). In addition, measured households from the second year did not use security lights during the night hours. Comparing the load duration curves for the third and after the third connection year, peaks with short duration are identified during the day and night hours, where the very large and intermittent peak powers are attributed to the use of productive appliances (wood cutter, in this case) and refrigerator. Table 6 presents the electrical devices ownership, grouped by connection years. The selected demographic and socioeconomic indicators of the measured households are presented in Table 8 in the Appendix.

Table 6
Comparison of mean electrical devices ownership of the measured households, by groups of connection years.

Group	1	2	3	4
Connection years	[0.25,1]	(1,2]	(2,3]	(3,8]
Battery radio	1.00	0.50	0.33	0.25
Electric radio	0.00	0.50	0.33	0.25
Sound equipment	0.00	1.00	0.33	0.75
Mobile phone	2.00	3.00	3.00	2.25
Television	0.00	1.00	1.00	1.00
DVD	0.00	0.00	0.00	0.25
Refrigerator	0.00	0.00	0.00	0.25
Electric iron	0.00	0.00	0.00	0.50
Electric kettle	0.00	0.00	0.33	0.00
Hairdryer	0.00	0.00	0.00	0.50
Productive appliances (wood cutter)	0.00	0.00	0.00	0.50
Lightbulbs	5.00	2.00	3.33	3.75
Security lights	1.00	1.50	2.67	3.25
Power rate lightbulbs (Watts)	25.00	16.50	17.33	21.50
Power rate security lights (Watts)	25.00	43.50	34.67	23.00

Discussion

Energy access transitions and their influence on the electricity consumption

Concerning the different theories of energy transition in rural areas, it was found among the samples that they tend to reduce their consumption of conventional fuels - especially kerosene for meeting their lighting needs, as they get access to electricity in different forms. However, for cooking there is more resistance for transitioning from firewood to a cleaner fuel. Evidence was found highlighting the positive impacts of the integration of off-grid renewable energy technologies as a transitional step in the energy access ladder. Furthermore, this study suggests that the current households' electricity access level – whether they have access to a SHS or do not have access to any source of electricity, has an effect not only on grid-electricity adoption, but also on their future electricity consumption once they get electricity access and in the consumption of other fuels. In Lee et al. (2020a,b) authors discuss that off-grid renewable energy technologies may “leapfrog” grid-electrification, and mention the rapidly increasing penetration of the SHS sector's in sub-Saharan Africa. Certainly, the results in this study present evidence that households that have a SHS are more likely to have already better socioeconomic improvements before getting grid-electricity connection, and will tend to consume 9 kWh/month more electricity, as they will acquire more power-consuming appliances when they get grid-electricity connection. These factors make them undoubtedly attractive as potential customers for electrification projects. Moreover, the overall benefits of rural electrification are evident as the households' quality of life improves in different aspects; in this study, it is especially represented in their usage of cleaner fuels for cooking, their reduction of kerosene

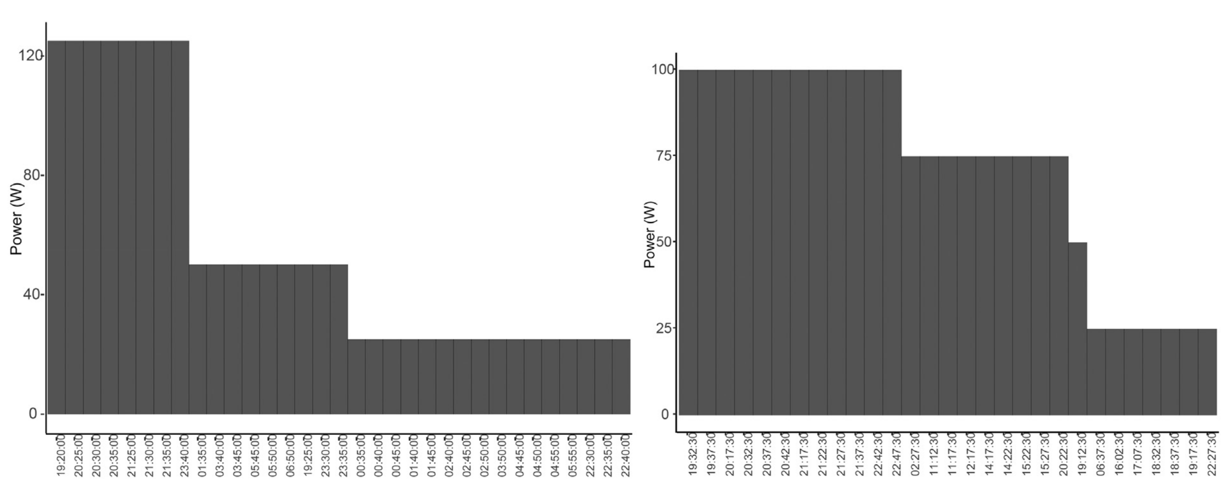

Fig. 7. Aggregated load duration curve for first group (left) and second group (right).

consumption for lighting, and their access to new sources of income other than agriculture.

The role of women as decision-makers towards accelerating a clean energy transition

Results present evidence that female-headed households have the least access to electricity grid connection, as well as the least access to secondary and superior education, among other socioeconomic indicators. However, results suggest that female-headed households are the ones willing to move on to cleaner fuels – especially for cooking, even in the cases where they have no electricity access at all. In addition, once they get access to grid-electricity female-headed households double the share of male-headed for the adoption of clean cooking fuels among the samples. This tentatively can be an effect of their constant exposure to the pollution of conventional fuels' combustion, as well as the time it costs them to collect the fuels. Their main barrier might be their acceptance in the society as formal income-earning actors, as so far their conditions limit them to carry out mostly low-income home-based jobs that put them in a disadvantaged position and makes them unattractive as potential electricity customers.

Post-electrification patterns

Electricity consumption tends to increase at an average rate of 12.7% with the connection years; however, the consumption peak after they get access to grid-electricity is perceived from the second to the third year, with an increase of 32.1% in electricity usage. This increase is related to the acquisition of large appliances, which might be a result of having the highest rates of owning a business at home, dedicating their time to other sources of income, as well as having savings for reducing their kerosene consumption since they were connected to the grid. The measured load profiles and survey results suggest that during the first and second years of connection the electricity consumption of rural households is mainly linked to the use of lighting and small appliances, such as radios, televisions, and mobile phones. While after the third year, the use of other high power-consuming appliances for short periods during the day is evident. Increasing the security in their houses as their socioeconomic conditions improve seems to be a priority for rural households, as the ownership of security lights tends to increase along with the connection years, and it was found to be one of the most important determinants for electricity consumption.

Certainly, the unreliability of the electricity grid infrastructure in developing countries is a significant drawback when it comes to deploying new connections. In Kenya, the electricity grid presents having frequent breakdowns, voltage drops, and a long outage restoration time (Moner-Girona et al., 2019). From the analysis presented, it is important to note that households' electricity consumption increases with the years as they acquire more power consuming devices; however, households are more dissatisfied with their electricity supply, as they also report at least six blackouts of more than 30 min per month. Considering the results from Table 5, their consumption of kerosene as a backup system also increases with the years, being households with more than three years of connection the largest consumers of kerosene among all grid-connected households; nevertheless, it is important to highlight that they consume 46.7% less than those without electricity access (NA households). This analysis suggests that the unreliability of the electricity grid-infrastructure represents a step back in the energy ladder, meaning that households gradually increase the consumption of the fuels they were using before getting connection to the grid.

Study boundaries and further developments

As with all survey-based studies, this research is subject to human-response bias that may cause alterations in the results. However, the questionnaires and the field interviews were carefully designed to minimize this bias, for example, focusing more on physically observable indicators of socioeconomic conditions, rather than on an ambiguous quantity as the income. In the case of determining the fuels consumption, the questions were directed to the amount of money they spend rather than on consumption quantities, as people are likely to give more accurate numbers when it comes to their expenses. Since households included in the study were not followed-up in time, a cross-sectional analysis was carried out among sample groups. For this reason, the results presented are based on found correlations, while causal effects are disregarded. Lastly, even though the number of samples was carefully calculated and households under the same environment considered as representative were selected for inclusion, it might be relatively small compared to the Kenyan rural population. However, the results obtained are aligned with results from studies with larger amount of samples, which increases the reliability of the study. For further developments, this study can be extended to other regions in Kenya or other countries in sub-Saharan Africa to compare the clean energy transition path and the effects of rural electrification under different environments. Specially, it could be interesting to observe how the reliability of the electricity grid infrastructure plays a role in the rural electrification aftermath, and how different national support programs, policies and demand-stimulation initiatives have an impact on households' electricity consumption over the years.

Conclusions

This paper presents a comprehensive analysis of the path towards a clean energy transition in rural areas, having evidence of representative households in Kenya. Filling in the knowledge gap of mapping the potential energy access ladder in rural areas, from the time that households do not have electricity access at all, to when they are finally connected to the national electricity grid; considering the intermediate access to an off-grid renewable technology, as well as the post- electrification years. The determinants of grid-electricity and solar home systems' adoption were identified, finding that factors such as belonging to a village included in Last Mile Connectivity Project, the share of grid-connected households, having good quality housing materials, and having a male household head will increase the probabilities of grid-electricity adoption. While increasing the electricity price will have a negative effect on these probabilities – having a greater impact on households without any source of electricity access with a reduction of 5%, together with the unreliability of the electricity supply, reducing the probabilities of adoption to 22% for households that own a solar home system. On the other hand, the adoption of solar home systems is mainly affected by the age of the household head; while younger household heads will be 99.4% more likely to adopt these systems.

Households that had access to a solar home system before getting electricity grid connection are likely to consume more electricity – 9 kWh/month more than households that did not have access to it. The ownership of security lights, household size and having access to clean cooking fuels were found to be the most significant determinants for electricity consumption among connected households. An important finding is that women as decision-makers have an important role in the clean energy transition of rural areas, as female-headed households are keener to adopt cleaner fuels at early stages such as SHS for electricity and gas for cooking; however, most of them lack access to grid-connection. As post-electrification effects, evidence suggests that after grid-connection, the electricity consumption tends to increase at an average rate of 12.7% with the years; however, the consumption peak is observed to happen from the second to the third connection year. The evolution of electricity usage can be clearly identified from the measured load profiles. During the first two years households use electricity mostly for lighting and small appliances, while in the third and fourth year more power-consuming appliances are acquired. The unreliability of the grid infrastructure can represent a step back on the energy ladder, as households tend to increase again their consumption of kerosene over the years at an average rate of 22.3% to cope with the frequent blackouts. However, the largest increase measured is still 46.7% less than what households without electricity access currently use for their lighting needs.

These results can provide insights to policymakers and project developers about what would be the determinants of the future consumption of households that do not have electricity grid access yet, as well as the drivers for SHS and grid-electricity adoption, contributing to understand the transformations towards reaching a clean energy transition in rural areas of developing countries. By presenting a comprehensive analysis of the impact of having intermediate access to a solar home system on the post-electrification consumption behaviors and the role of women in the energy transition, the findings can be used as reference for identifying the adoption and consumption patterns of other rural communities, enhancing the deployment of energy access solutions. These findings, as well as the detailed data collected from the representative villages can be potentially applied for further analyzing and improving energy access policies and measures in Kenya in order to accomplish the Sustainable Development Goal 7, dedicated to ensuring global access to clean, sustainable and affordable energy by 2030.

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.

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Appendix A

Table 1
Comparison of socioeconomic characteristics at a household level of county and rural Kenya based on the latest Household National Census data (KNBS, 2019).

	Busia	Siaya	Rural Kenya
Education (completed secondary school)	19.1	19.1	21.0
Housing			
Good quality roof material	87.2	93.5	86.4
Good quality walls material	29.7	29.7	26.2
Good quality floor material	37.8	44.0	35.1
Good quality source of drinking water	5.6	5.5	13.2
Cooking fuel			
Electricity	0.5	0.3	0.4
Gas	6.0	6.0	5.6
Firewood	73.4	72.4	84.1
Charcoal	18.0	18.8	7.7
Solar	0.2	0.2	0.2
Lighting fuel			
Electricity	26.1	19.7	26.3
Kerosene (paraffin)	27.3	24.0	23.7
Gas	0.1	0.1	0.2
Solar	37.9	50.8	29.9
Torch/solar charged	5.9	2.8	8.1
Candle	1.4	1.4	1.0
Battery car	0.3	0.5	0.6
Generator	0.0	0.0	0.1
Assets			
Mobile phone ownership	38.4	44.1	40.5
Internet access	13.5	14.9	13.7
Radio ownership	54.5	65.5	58.5
Computer	3.7	4.2	3.0
Television	27.2	28.3	26.9
Refrigerator	3.7	4.0	2.4
Bicycle	34.4	32.7	15.6
Motorcycle	11.8	11.8	10.8
Car	2.9	2.9	3.5

Table 2
Village information obtained from interviews with village elders and national census data (KNBS, 2019).

Village	Sub-county	County	Population density[a] (people/km^2)	No. schools	No. medical centers	No. transf.	Time of installation of transformers[b]
Ukwala	Ugenya	Siaya	415	1 primary, 1 secondary	None	2	1 from LMCP (2 years), 1 (more than 3 years)

(continued on next page)

Table 2 (*continued*)

Village	Sub-county	County	Population density[a] (people/km^2)	No. schools	No. medical centers	No. transf.	Time of installation of transformers[b]
Umer B	Ugenya	Siaya	415	1 primary	1 dispensary	1	5 years
Umer A	Ugenya	Siaya	415			2	1 from LMCP (2 years), 1 (5 years)
Luru	Ugunja	Siaya	519	1 primary	None	[c]	
Koteko	Teso North	Busia	529	1 primary	None	1	From LMCP (2 years)
Akudiet	Teso South	Busia	555	1 primary	1 hospital	2	From LMCP (1 year)
Akoruf	Teso South	Busia	555	1 primary, 1 secondary	1 dispensary	1	From LMCP (7 months)
Emakina	Nambale	Busia	469	1 primary	None	1	2 years
Siribo	Butula	Busia	576	None	None	1	3 years
KanjalaB	Butula	Busia	576	1 primary	1 dispensary	3	1 (4 years), 1 (3 years), 1 (1 year)
KanjalaE	Butula	Busia	576				
SegeroC	Nambale	Busia	469	2 primary	None	1	2 years
Apokor	Teso South	Busia	555	2 primary, 1 secondary	1 dispensary	5	1 from LMCP (1 year), 4 (10 years)
Asinge	Teso South	Busia	555	3 primary, 1 secondary	1 dispensary	5	3 from LMCP (3 years), 2 from LMCP (4 months)
Kingandole	Butula	Busia	576	5 primary, 2 secondary	1 dispensary, 1 hospital	7	3 from LMCP (5 months), 4 (10 years)
Akites	Teso South	Busia	555	2 primary	None	2	1 from LMCP (4 years), 1 (more than 4 years)

[a] Sub-county value taken from 2019 Household National Census data.
[b] From the date of the interview.
[c] There was one in the primary school, but was removed by KPLC due to unknown reasons. They believe that they will be installing the transformer again, but they do not know when.

Table 3
Number of samples included in the household surveys by sampling group.

Village	No. samples	NA households	SHS households	Connected households
Ukwala	13	15%	39%	46%
Umer B	14	21%	21%	58%
Umer A	15	27%	13%	60%
Luru	12	25%	42%	33%
Koteko	15	33%	20%	47%
Akudiet	15	13%	7%	80%
Akoruf	12	17%	8%	75%
Emakina	19	16%	58%	26%
Siribo	17	35%	47%	18%
KanjalaB	15	33%	20%	47%
KanjalaE	15	27%	27%	46%
SegeroC	15	27%	7%	66%
Apokor	17	0%	6%	94%
Asinge	17	47%	29%	24%
Kingandole	18	11%	6%	83%
Akites	21	33%	57%	10%
Total	250	60	66	124

Table 4
Sampling details of households measured for electricity loads.

HH ID	Village	Connection time
1	Ukwala	1 year
2	Akudiet	2 years
3	Akudiet	3 years
4	Koteko	4 years
5	KanjalaB	3.5 years
6	KanjalaB	3.5 years
7	KanjalaB	8 years
8	Kingandole	2 years
9	Kingandole	3 years
10	Kingandole	3 years

Table 5
Comparison of mean socioeconomic conditions between electricity access level sample groups.

	NA	SHS	Connected
Housing and demographics			
Good quality walls material[(a)]	3%	24%	26%

Table 5 (*continued*)

	NA	SHS	Connected
Good quality roof material[(b)]	0%	0%	2%
Good quality floor material[(c)]	25%	47%	67%
Total number of rooms[(d)]	4.88	5.71	6.50
Household size	4.73	5.65	5.51
Age of household head	50.98	39.70	44.23
Female household heads	62%	61%	41%
Access to clean fuels for cooking[(e)]	0%	3%	7%
Access to secondary and superior education	7%	38%	40%
Main occupation from which household income relies			
Agriculture	98%	81%	76%
Manufacturing	0%	2%	2%
Education/health/scientific	0%	5%	8%
Trading	0%	9%	12%
Home business	2%	4%	3%
Assets			
Large appliances[(f)]	0.12	0.77	1.13
Small appliances[(g)]	1.82	3.03	2.78
Large livestock[(h)]	1.53	2.47	2.45
Small livestock[(i)]	1.02	1.74	1.78
Poultry	6.48	10.58	9.67
Cars	0%	5%	13%
Motorbikes	5%	39%	27%
Bicycles	52%	80%	77%

[a] Walls made of brick or cement.
[b] Roof made of concrete or tiles.
[c] Floor made of concrete or ceramic tiles.
[d] In rural Kenya, it is common to find that household members live in a compound formed by a number of "bomas" that act as independent rooms for different purposes. In the questionnaire, respondents were asked to give the number of rooms by category (bedrooms, living room, kitchen, etc.) instead of asking the number of bomas within the compound, this was done to avoid confusion as some bomas have more than one room. Then, these rooms were aggregated into a single variable.
[e] Clean cooking fuels consider Liquefied Petroleum Gas (LPG) and biogas.
[f] Television, DVD, refrigerator, sound equipment, sewing machine, portable computer.
[g] Electric and battery radio, mobile phone.
[h] Oxen, cattle.
[i] Goats, pigs, sheep.

Table 6
Comparison of mean socioeconomic conditions between groups of connection years.

Connection time (years)	[0.25,1]	(1,2]	(2,3]	(3,8]
Housing and demographics				
Good quality walls material[(a)]	10%	24%	15%	30%
Good quality roof material[(b)]	2%	0%	0%	6%
Good quality floor material[(c)]	56%	67%	71%	64%
Number of rooms[(d)]	5.71	5.96	6.30	6.49
Household size	5.36	5.66	6.86	4.90
Age	43.53	42.41	56.08	41.31
Female household heads	4%	28%	7%	24%
Access to clean fuels for cooking[(e)]	1%	1%	8%	17%
Access to secondary and superior education	30%	51%	37%	35%
Main occupation from which household income relies				
Agriculture	84%	88%	56%	57%
Manufacturing	0%	2%	2%	0%
Education/health/scientific	5%	3%	2%	11%
Trading	7%	7%	15%	31%
Home business	5%	0%	24%	0%
Assets				
Large appliances[(f)]	1.07	1.24	1.91	1.59
Small appliances[(g)]	2.78	2.91	2.72	2.49
Large livestock[(h)]	2.49	2.74	2.37	1.52
Small livestock[(i)]	1.85	2.09	1.33	0.96
Poultry	7.81	8.61	8.36	7.59
Cars	8%	3%	16%	11%
Motorbikes	19%	18%	58%	23%
Bicycles	73%	80%	64%	74%

Note: same as Table 5.

Table 7
Local markets average fuels price.

Fuel	Measure unit	Price	
		KSh	USD*
Firewood	Woodwork or *stere*[(a)]	20	0.2
Charcoal	Can (0.355 L)	20	0.2
Candles	Unit	2	0.02
Kerosene	Bottle (0.5 L)	50	0.5
Gas[(b)]	Tank refill	900	9
Electricity[(c)]	kWh	12.9	0.13

* The exchange rate from Kenyan Shillings (KSh) to US Dollars (USD) was taken as 0.01USD/KSh, considering the average rates when the fieldwork was performed.

a Firewood is often sold in woodworks or "stere", representing a unit of volume equal to one cubic meter.

b The price of the tank is not included, as it is assumed that people already have it and refill it each month.

c The electricity rate was estimated using an average of the electricity tariff for 2018/19 [tariff for 2018/19] for both categories of domestic consumers defined by KPLC based on the consumption units (kWh) per post-paid billing period or pre-paid purchased period. These consumers are the "lifeline" (those that do not consume more than 10 units), paying 10KSh/kWh, and the "ordinary" (those that consume more than 10 units, but do not exceed 15,000), paying 15.8KSh/kWh.

Table 8
Comparison of mean socioeconomic conditions of measured households between groups of connection years.

Group	1	2	3	4
Connection time (years)	[0.25,1]	(1,2]	(2,3]	(3,8]
Housing and demographics				
Good quality walls material*(a)*	100%	50%	33%	50%
Good quality roof material*(b)*	0%	0%	0%	0%
Good quality floor material*(c)*	100%	100%	100%	50%
Total number of rooms*(d)*	6	5.5	5.3	8.5
Household size	5	6	6.3	5.75
Age of household head	40	50	52	46.5
Female household heads	0%	50%	100%	50%
Access to clean fuels for cooking*(e)*	0%	0%	33%	75%
Access to secondary and superior education	0%	0%	33%	50%
Main occupation from which household income relies				
Agriculture	100%	100%	66%	50%
Trading	0%	0%	0%	50%
Home business	0%	0%	34%	0%
Assets				
Large livestock*(f)*	2	4	1.67	2.5
Small livestock*(g)*	0	1.5	1	0.5
Poultry	21	15.5	8.67	17.5
Motorbikes	0	0	0	0.25
Bicycles	0	1	1.33	0.75

Note: same as Table 5, except for (f) Oxen, cattle. (g) Goats, pigs, sheep.

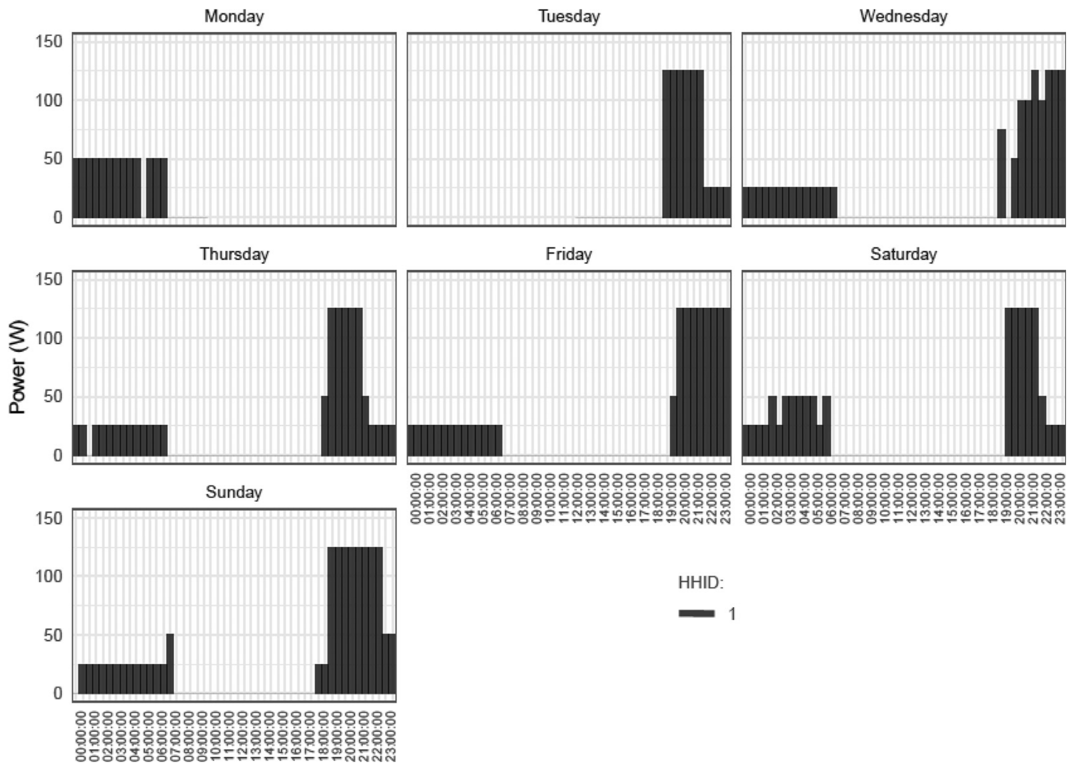

Fig. 1. Daily hourly load profiles for households belonging to the first group. See reference in Table 6 in the text and Table 8 of the Appendix.

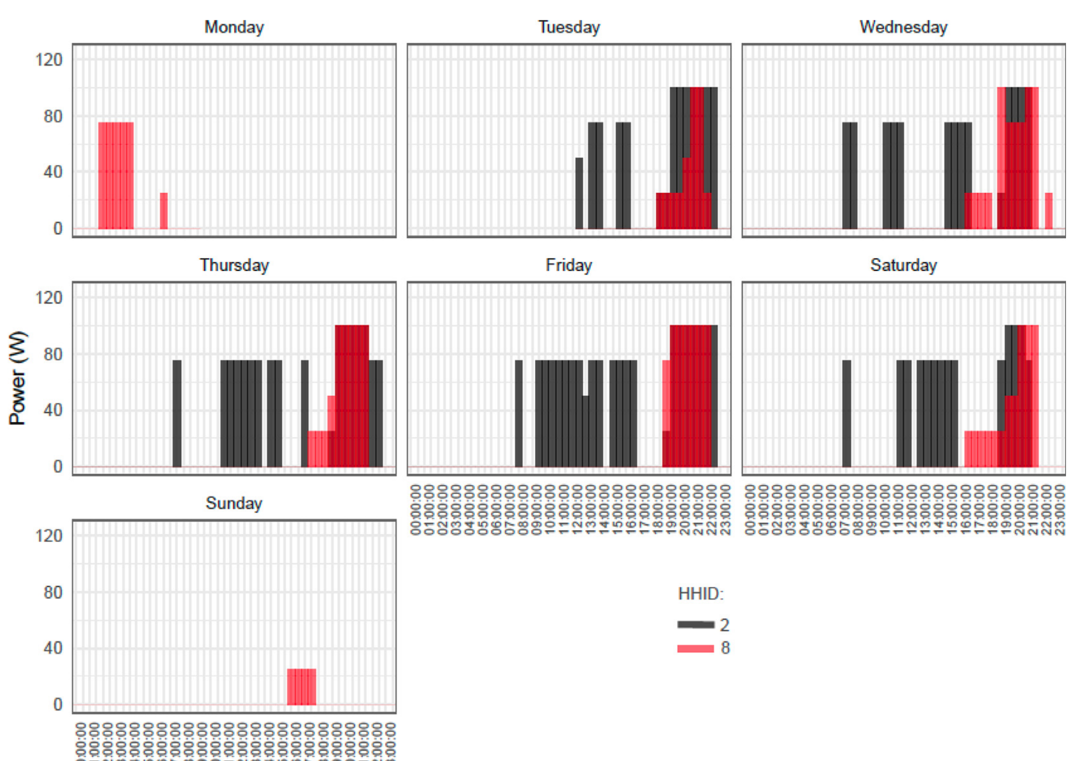

Fig. 2. Aggregated daily hourly load profiles for households belonging to the second group, in black for HH2 and in red for HH8. See reference in Table 6 in the text and Table 8 of the Appendix.

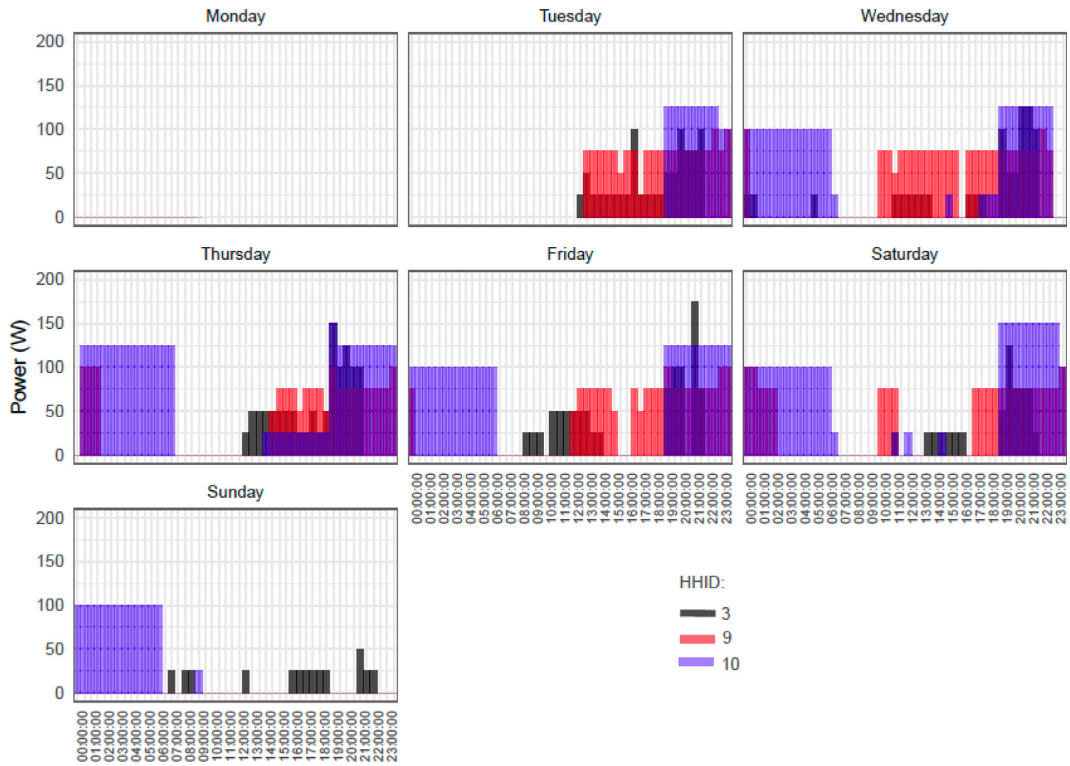

Fig. 3. Aggregated daily hourly load profiles for households belonging to the third group, in black for HH3, in red for HH9, and in blue for HH10. See reference in Table 6 in the text and Table 8 of the Appendix.

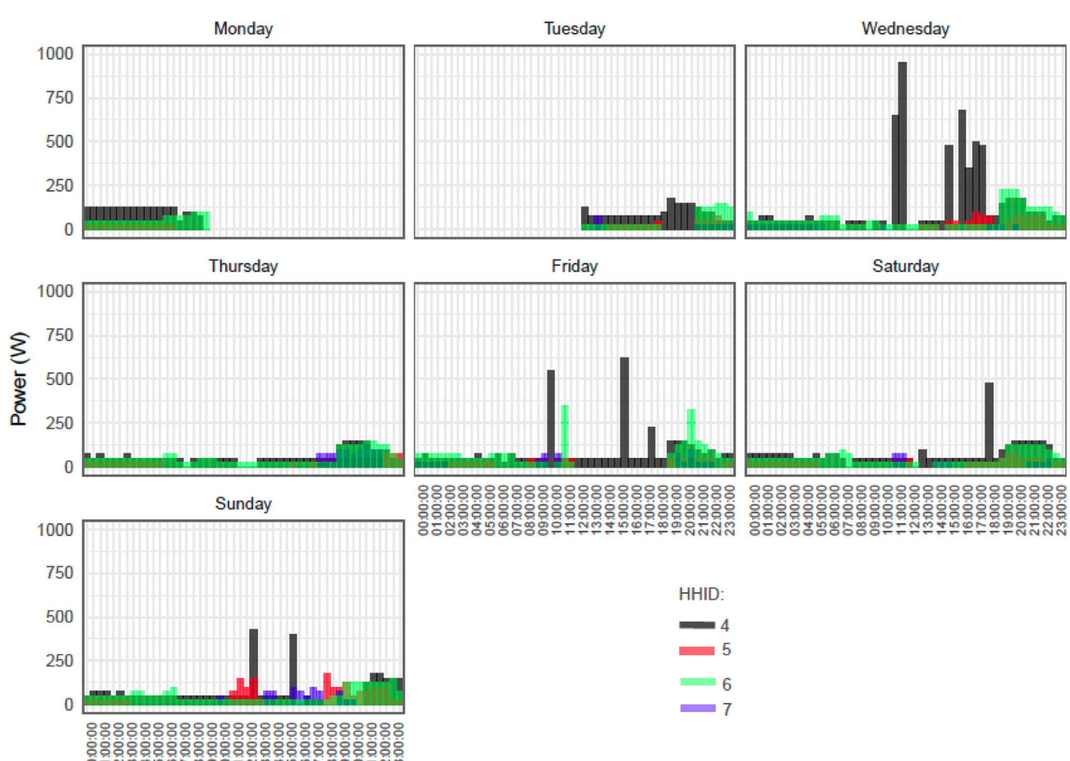

Fig. 4. Aggregated daily hourly load profiles for households belonging to the fourth, in black for HH4, in red for HH5, in green for HH6, and in blue HH7. See reference in Table 6 in the text and Table 8 of the Appendix.

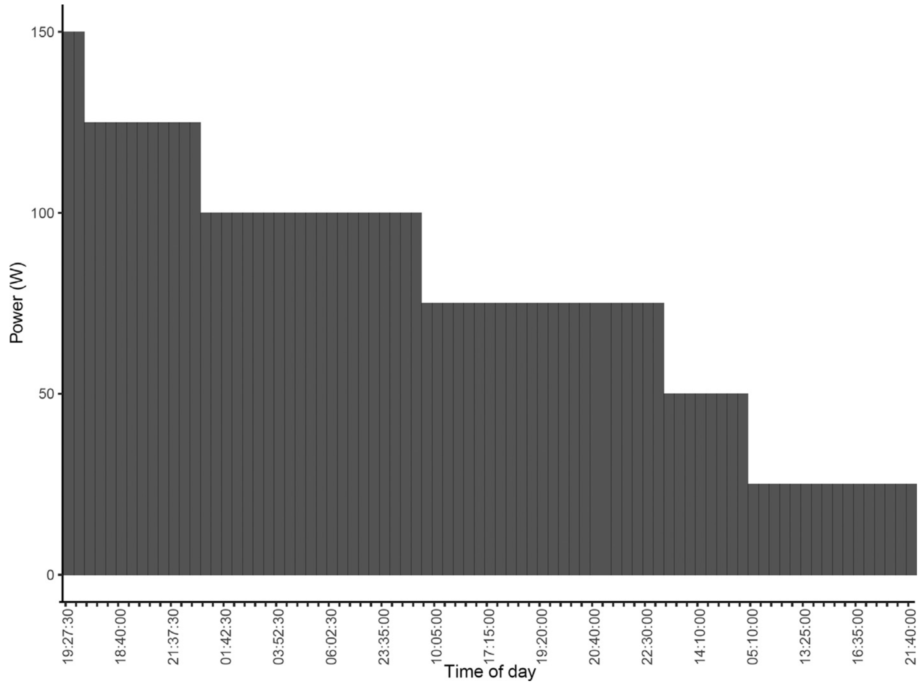

Fig. 5. Aggregated load duration curve for third group.

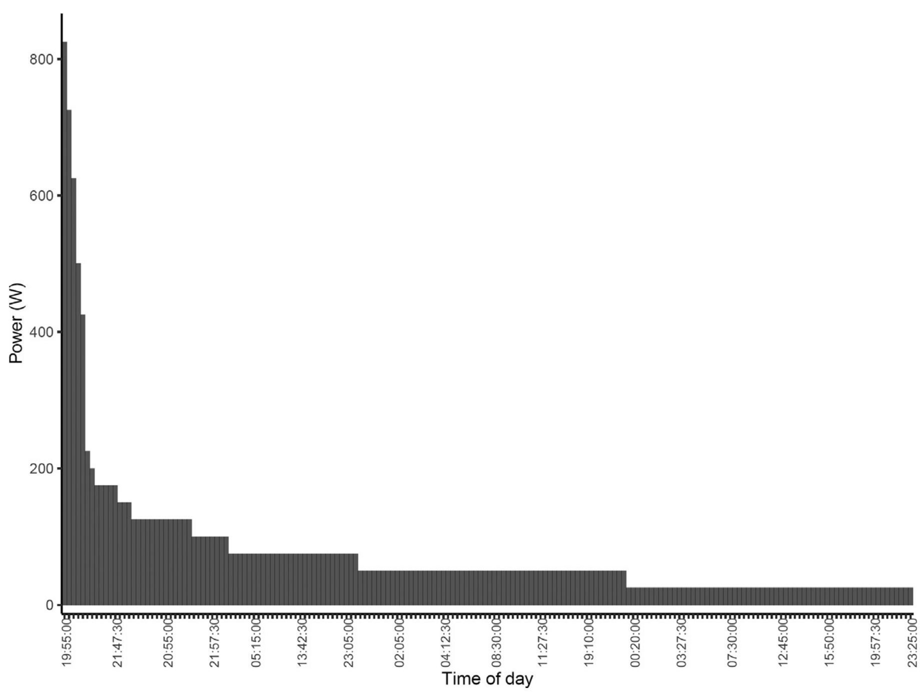

Fig. 6. Aggregated load duration curve for fourth group.

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