To climb or not to climb? Investigating energy use behaviour among Solar Home System adopters through energy ladder and social practice lens.

Abstract

Solar Home Systems (SHSs) and other off-grid solutions have shown promise in addressing the energy access gap for those with no or unreliable grid services. With that promise comes the expectation to boost socio-economic well-being of newly-connected households, who will continue climbing up the energy ladder. Despite the growing appreciation for the need to go beyond the techno-economics of energy access, and the recognition of the value of socio-technical systems perspective, the wider sociology of energy consumption and behaviour among adopters of off-grid solar solutions has been poorly explored. In this paper, we apply the Social Practice Theory (SPT) and the energy and solar energy ladder framework to analyse energy consumption and the changing social practices of SHSs users in Rwanda. We find that social practices change dynamically and depend on available appliances, whereas energy consumption follows a complex path but does not increase in a linear manner with time or more appliances. Insights can prove useful for public and private agencies working on off-grid electrification, offering a new perspective on the energy and solar energy ladder concepts while also showing the importance of social aspects of energy access even at relatively low levels of provision currently offered by SHSs.

Introduction

Over one billion people are still unconnected to modern energy sources, over half of them in Sub-Saharan Africa (SSA) alone (IEA, 2016). Solar Home Systems (SHSs) and other distributed off-grid solutions (such as solar lanterns) have shown promise in addressing the energy access gap by helping tackle the problem of energy distribution to those with limited or no access to the grid due to high costs, remote locations and insufficient demand making grid extensions financially unviable (Hogarth & Granoff, 2015), as well as to another one billion who are grid-connected but experience unreliable, intermittent services (Lahimer, et al. 2013), often consuming little to no energy at all (Lee et al., 2017). Bloomberg New Energy Finance (BNEF) (Bloomberg New Energy Finance, 2017) estimate that at least 89 million people across the developing world have one or more solar lighting products and one in three off-grid households will rely on off-grid solar PV solutions by 2020. Sales in the last few years have been steadily gaining pace, particularly in leading markets of East Africa and South-East Asia (SEA), where a range of off-grid solar products and services have been actively included in the electrification plans (Dalberg Advisors & Lighting Global, 2018). Notable examples include Kenya, Tanzania and Rwanda, which follow perhaps one of the most successful SHSs programmes to date in Bangladesh where over four million systems have been installed as part of the country's Infrastructure Development Company Limited (IDCOL) plan for off-grid regions (IDCOL, 2017).

The growing importance and scale of off-grid solar electrification in SSA and SEA have attracted increased attention in the academic research community. Some of the key questions to which answers have been sought include those around technology design (e.g. Chowdhury & Mourshed, 2016; Zubi et al., 2016), financing of and for the off-grid sector (e.g. van der Vleuten et al., 2007; Mainali & Silveira, 2013; Pode, 2013; Bloomberg New Energy FInance, 2016; Quansah et al., 2016), designing business models which best suit the poor (e.g. Rolffs et al., 2014; Hirmer & Cruickshank, 2014; Tawney et al., 2014; Krithika et al., 2015; Reddy, 2015), and the affordability of solar solutions with a focus on willingness to pay (WTP) (e.g. Hogarth & Granoff, 2015; Grimm et al., 2016). Additionally, it has been debated whether such small-scale solutions can meet the growing energy demands at their current capacity (typically 11 to 100 Wp), supporting productive uses and spurring economic growth (Azimoh et al., 2015; Brew-Hammond, 2010; Jacobson, 2007; Prasad, 2007). Aklin et al. (2017) have argued that SHSs benefit end-users by displacing kerosene, however, they have questioned if the wider socio-economic impacts are indeed observed based on the weak evidence found in four reviewed randomised controlled trials (RCTs) in South Asia and Africa. As contended by Wamukonya (2007), solar systems, with all their advantages and disadvantages, are not a panacea to the energy challenge and more questions need to be raised to understand the socio-cultural and economic priorities of rural households. This is of particular significance given the widely acknowledged energy stacking practices among not only low income, but also other layers of society in developing countries. Contrary to the idea of climbing the hypothetical energy ladder, which assumes that both traditional and modern forms of energy are available and households will choose to switch to the next best source as soon as it becomes available and they can afford it (e.g. Masera et al., 2000), it has been shown that both rural and urban households follow more complex energy transition trajectories and tend to rely on more than one energy source as their income increases and improved solutions become available, a term that has been coined as 'energy stacking' (see Figure 1) (Tait, 2017; van der Kroon et al., 2013; Kowsari & Zerriffi, 2011; Nansaior et al., 2011; Masera, Saatkamp & Kammen, 2000) or 'energy staircase' (Harrison & Adams, 2017).

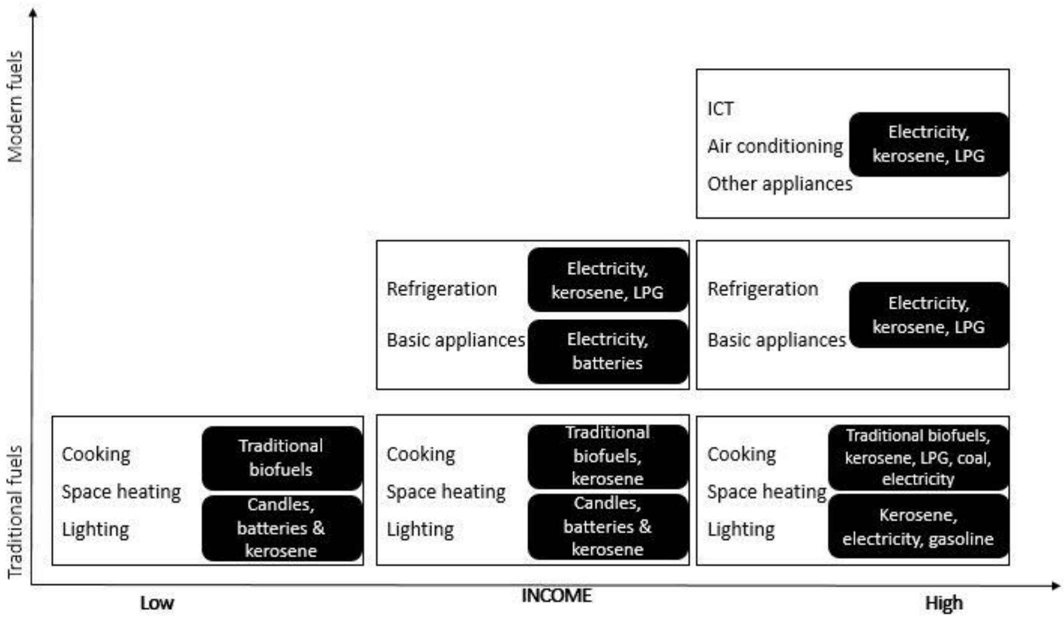

Figure 1. Energy stacking visualisation. Different energy sources continue to be used over time and regardless of income level. (Source: Kowsari & Zerriffi, 2011)

In light of the expanding off-grid solar energy market, the idea of a solar energy ladder has emerged (e.g. RMI, 2015). It assumes that households will gradually progress from small-scale solar technologies, such as solar lanterns, to bigger SHSs, adding new appliances and increasingly using more energy, eventually switching to solar micro/mini-grids and, if available, the grid (Chattopadhyay et al., 2015). Within that notion, there is an expectation that such progression will automatically contribute to boosting the socio-economic condition of the households concerned (e.g. Kanagawa & Nakata, 2008). To date, studies on the subject have been scarce and present a mixed-results evidence (Aklin et al., 2017; Aklin et al., 2017; Lee et al., 2017; Lenz et al., 2017). Harrison & Adams (2017) demonstrate that households familiar with smaller solar products are more likely to purchase bigger solar systems, having become familiar and confident with the entry-level solar product. Stojanovski et al. (2017) examined approximately 500 early adopters of SHSs and found a significant reduction in the use of kerosene, which points towards a step up the energy ladder for lighting, however, they did not observe substantial income-generation resulting from the use of SHSs. The range of used appliances was also limited. In their study of large-scale infrastructure, Lenz et al. (2017) investigated the impact of grid access on households 3.5 years after being connected and found that even after that time energy consumption and uptake of appliances remained low, with no significant impacts on income. These findings challenge the idea that energy consumption increases over time, even when the energy source is, in theory, unlimited and cost-competitive.

While the energy ladder concept recognises the complex social processes which underpin energy stacking behaviour, such as socio-economic and cultural preference for cooking fuels, often associated with history and tradition (van der Kroon et al., 2013), it still primarily focuses on the techno-economics of energy access. A similar trend has developed in the exploration of the off-grid solutions. As pointed out by Rolffs et al. (2015), the dominant considerations of the provision of renewable, off-grid access options have typically been around two-dimensional categories of finance – technology and economics – engineering, often missing the social contexts. A relatively early study that stands out was carried out in Papua New Guinea by Sovacool et al. (2011) and through the application of socio-technical change showed how the lack of understanding of social barriers might hinder the success of SHSs adoption and sustainability. In a recent study of rural community energy projects, Cloke et al. (2017) put forward a Social Energy Systems (SES) approach for the exploration of scalable delivery models of renewable energy technologies (RET) which tends to the particular needs and aspirations of end-users. In doing so, it moves away from the two-dimensional, techno-logic of understanding the changing landscape of energy transitions in the developing context. In a similar study of a village-level solar power project in Kenya, Ulsrud et al. (2015) have applied a socio-technical model design paying close attention to the socio-cultural context and end-users' challenges, demonstrating the value of such approaches in building sustainable, context-relevant off-grid energy systems. Similarly, Urmee & Md (2016) have advocated the need to pay closer attention to the social, cultural and political issues while designing off-grid renewable energy programmes, calling for community involvement and the inclusion of community needs in energy policy work.

Despite the growing appreciation for the need to go beyond the techno-economics of energy access, and the recognition of the value the socio-technical systems perspective offers by putting the society and, effectively, the end-user's needs en par with the technology, the wider sociology of energy consumption and behaviour among adopters of off-grid solar solutions, including SHSs users, has been relatively poorly explored. Studies have mostly focused on understanding the experience of end-users concerned by focusing on the array of impacts, with key socio-economic metrics including health improvements due to smoke reduction, extended productive and study hours, savings on energy expenditure and access to phone charging and information (Avila et al., 2017; Harrison & Adams, 2017; Mishra & Behera, 2016).

Given the rapid expansion of off-grid electrification and the predicted continuation of high levels of adoption of off-grid solar PV for energy access, it is important to better understand the energy behaviour as experienced and practiced by end-users. While the energy ladder framework offers a lens of looking at energy consumption and associated behaviours (e.g. appliance adoption), the social practice theories (Shove et al., 2012; Reckwitz, 2002) provide a framework for deeper exploration of social aspects of energy use in households with off-grid solutions. So far, they have predominantly been used in the context of energy sustainability transitions in the developed countries, particularly in Europe and the US (e.g. Smale et al., 2017; Bulkeley et al. 2016; Lipschutz, 2015; Higginson et al., 2013). Within that discourse, Tang & Bhamra (2008) have argued that by understanding the energy use behaviour, i.e. how people use electrical appliances, can inform product designers and equip them with tools to plan and shape how consumption occur, thus leading to more sustainable use practices.

In this paper, we contribute to the limited existing knowledge on the social dimensions of energy use, looking at changing social practices associated with gaining access to off-grid energy services. We also look at energy consumption as reported by end-users and as recorded by SMART[1] SHSs (referred to as SHS going forward) via real-time remote monitoring in order to gain insights into what appliances and when are used in the household, whether there are any differences in the level of consumption across different groups, depending on the length of time they have been using the systems for and the appliances owned. By doing so, we aim to answer the question on whether there is an observed increase in energy consumption and appliance adoption as would be expected according to the solar energy ladder framework, and how social practices change over time and with more available appliances. We also put to test the energy stacking behaviour, particularly in the case of off-grid consumers using SHSs for access to electricity, without the option to support cooking needs.

We argue that social practices change dynamically across the adopters of SHSs and depend on the available services offered by various appliances, which are the drivers of practice shifts contributing to improved well-being of household members. Just as the practice change is a dynamic process, so is energy consumption which does not increase in a linear way and follows a more complex trajectory over time and according to different appliances available. We also observe low rates of additional appliance adoption and relatively low overall levels of energy consumption, in line with some of the existing evidence challenging both the energy ladder and solar energy ladder notions referred to earlier in this section. We notice that income generating applications can maximise consumption even with only the basic appliances offered by SHSs providers. Finally, we observe that energy stacking behaviour is prevalent among adopters of SHSs.

For the purposes of this study, we define the hypothetical energy ladder as a move from inferior (traditional) to superior (modern) energy sources over time and as they become available and affordable to the adopters, and the hypothetical solar energy ladder as an increase, over time, in the utilisation of off-grid solar energy in terms of power consumed and appliances adopted, as well as a move up from smaller solar systems (e.g. solar lanterns) to bigger ones (e.g. SHSs).

This study presents a unique insight into the energy use patterns thanks to the real-time use data collected through SHSs under investigation, while at the same time placing energy use in the context of social practices, demonstrating the complex interplay between the two in the case of off-grid solar energy. To the best of the authors' knowledge, such studies have not been conducted before and if so, they have been scarce and readily identifiable among the existing literature.

In section 1 we briefly look at the social practice theory focusing on behaviour, including some of their applications in energy research. Section 2 outlines research methods followed by section 3 which presents the findings where we analyse the self-reported and remotely-monitored energy usage patterns, as well as the shifting practices of energy use among SHSs adopters. Section 5 offers further discussion and conclusions.

1. Social practice theory and energy access

Social practice theory was first put forward by Schatzki (1996) and subsequently elaborated by Reckwitz (2002), drawing on the work of Bourdieu (on habitus and practice) and the structuration theory formulated by Giddens (1984) which talk about the role practices and routines play in structuring social systems and daily lives[2]. A practice, in simple words, is a routinized form of behaviour

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[1] SMART stems from SMART Solar platform which is a platform built by the SHS provider to remotely monitor their SHSs. SMART is not an acronym in this name.

[2] For a comprehensive overview of social theories of practice, see for example Bartiaux (2012) *Researching on energy-consumption practices: Adding social interactions and geographical characteristics to the social theories of practice*.

(Reckwitz, 2002). What is shared by the different strands of practice theories is the collective nature of practices (Bartiaux, 2012) where individuals are the 'carriers', or hosts, of many different practices and the units in which bodily-mental routines coexist, creating a "temporally and spatially dispersed nexus of doings and sayings" (Schatzki, 1996: 89) which constitute a practice. In early conceptualisations, practices were conceived of as entities and performances existing outside of the physical, material world. However, what gradually gained recognition in the understanding of social practices was the need to apprehend material configurations (Schatzki et al., 2001). In their work *The Dynamics of Social Practice*, Shove and colleagues (2012) emphasise the "[…] constitutive role of things and materials in everyday life" (p. 9). In that, they follow Latour's view that artefacts "[…] are in large part the stuff out of which socialness is made" (ibid.) and that living and non-living things are active agents in the society, as posited in the actor-network theory (ANT) (Latour, 2005)), organising, structuring or even preventing some practices. They see people as agents and 'practitioners' who combine three elements which make practices: materials (the physical things and objects - the 'hardware'), competences (skills and know-how - the 'software'), and meanings (symbolic meanings, ideas and aspirations) (Shove et al., 2012:14).

Just like cooking, playing football or washing clothes are social practices, so is energy use. According to Lipschutz (2015) we 'practice energy' by engaging in various practices which require its provision, for example heating or cooling. It is about "[…] all the different things that people do at home which consume energy […] as part of a collective structure in which some common rules are followed" (Gram-Hanssen, 2014:94). The focus is on activities, how we undertake them and what elements they comprise of.

Social practice theories have been widely applied to the study of consumer behaviour and behavioural change, particularly towards triggering more sustainable levels of resource consumption in the industrialised society (Higginson et al., 2013; Browne et al., 2013). In energy research, the approach has been commonly used in looking at energy security and low-carbon transitions to find ways of aligning practices to new regulations or rationales (e.g. the use of smart meters for more efficient and responsible energy consumption (Smale et al., 2017; Gram-Hanssen, 2014) or use of solar PV energy in grid-connected households for the 'greening' of energy sourcing (e.g. Sangroya & Nayak, 2017)). One recent study of middle-income households in Pakistan used SPT to better understand the connection between practices and the 'uncanny' energy demand (Khalid & Sunikka-Blank, 2017), which is the only application in the developing context known to the authors, though focusing on relatively wealthy households with access to the grid electricity supply. Yet in countries undergoing early stages of electrification, often relying on mixed energy systems deployment (including grid and off-grid, such as is the case of Rwanda), practices are changing at a rapid pace too: not only in terms of what energy is consumed for and how, but also in regards to the reconfiguration of daily routines and practices around energy consumption, including family socialising or shifting household chores from early morning hours to evening. What Shove (2017) refers to as "devices, infrastructures and resources" in the case of off-grid electrification in low-income settings might be limited to fewer devices or resources as SHSs have a capped capacity (depending on the panel and battery size) and typically there are only basic appliances that come with them, such as radios, phone charging ports, lights, fans, TVs, shavers, etc.

2. Methods

This research has been designed as a case study and investigates users of SHSs as offered by one of the companies[3] operating in Rwanda (from here on referred to as the provider). The choice to focus on customers of one of the operating providers, rather than multiple ones[4], was dictated by the ability of the researcher to access all real-time end-user data, which is a unique feature of the systems currently offered by as few as a couple of SHS providers in this domain. Through collaboration with the provider, access to conduct further data collection was also enabled. Although it poses a limitation to the study as products and services of only one provider are investigated, it has allowed for a novel research opportunity combining various data sets, including usage data which is otherwise difficult to obtain. The study also encompasses a range of system types (packages) which cover the most common SHSs and their average capacity across the whole market, therefore we believe that our sample can be considered to be representative of the average experience of a SHS user in Rwanda.

A case study, which is an empirical enquiry that investigates a contemporary phenomenon in a real-life context (Yin, 1994), offers a research design suitable for complex social phenomena, allowing for exploration of multiple variables and sources of evidence (Baxter & Jack, 2008). It has been adopted in the exploration of competing concepts of energy ladder, solar energy ladder and energy stacking, and changing social practices among users of SHSs as all present a complex social phenomena in a real-life context and benefit from combined quantitative and qualitative data.

The empirical data used in this paper makes part of a wider case study of SHSs users in Rwanda conducted by the lead author between 2016 and 2017. Households were the main point of investigation. This research assumes a mixed methods approach, combining both qualitative and quantitative research methods. Browne et al. (2013) have argued that most studies of practice have been largely qualitative, leaving a gap in providing quantitative evidence needed for large-scale strategic planning and to inform policy making. This study attempts to take a more balanced approach, utilising quantitative survey, self-reported and actual consumption data which, in line with Gram-Hanssen's (2014) argument, are valuable to combine with qualitative data in order to check the objective measurements against the subjectively perceived energy behaviour. Quantitative data on energy usage and previous energy sources, as well as new appliance adoption, have provided evidence for exploring the concept of energy ladder as applied to SHSs users. It was collected through household and telephone surveys (a total of n=265 respondents, each one representing one household) and included self-reported energy usage data where respondents declared what appliances they use at what times on an average day. This set of data offers new insights into how routines around the use of available appliances shape up in households mostly relying on SHSs for electricity. Actual, energy consumption data, which was compared among survey participants according to the length of system use (Group 1 using the system for more than a year, Group 2 using the system for more than 6 months and less than one year, and Group 3 using the system for less than 6 months) was obtained from the SMART Solar platform (n=217[5]) which is embedded in the systems and monitors power consumption in real-time. Going forward, we will refer to the three Groups as Group 1, Group 2 and Group 3.

Households participating in the survey were selected via purposive sampling according to the system package they owned (which varies in the number and type of appliances rather than capacity: all 50W

[3] A private provider of SSHSs. They design and manufacture the systems, distributing and financing them in Kenya and Rwanda where they are sold on a PAYG basis.

[4] There are numerous SHSs providers in Rwanda, with approximately 4-5 key players. One of them is the provider whose customers this research focuses on.

[5] Consumption data was not available for all 265 units. Total SMART Solar data sample was n=217. There were n=64 in Group 1, n=83 in Group 2 and n=70 in Group 1.

with a 12V 17Ah battery) in order to get a diverse range of system sets (see Tables 1 and 2 in Section 4 for a breakdown of appliances and systems in the sample). The period of time since adopting a system (Group 1, Group 2 and Group 3) was taken into consideration to understand whether there are any differences in the amount of energy consumed depending on the length of use and thus test whether energy use increases over time. Survey participants were recruited from the Northern and Western provinces of Rwanda where the highest number of customers who had been using a system for over a year were available (at the time of data collection between July and September 2016). As it is a relatively new market, there were only a limited number of users who had been using their systems for an extended period of time in any given community or region of the country. The overall saturation of SHSs is still relatively low and on average only a few SHSs are used in any given village or community across the country. Households participating in energy mapping discussions were selected purposively according to accessibility from the Northern, Western, Eastern and Southern provinces of Rwanda.

73.2% of survey respondents were male, 26.8% female. Average age was 41 years, ranging from 19 to 94. The average household size among participating households was 5.64 members (std. dev. = 2.05), with the average distance to the nearest grid of 36.5 minutes (walking) (ranging from being right 'under the grid' to living over 5 hours away by walk). 9 households were connected to the grid network. 44.5% lived below $2.50/day[6].

Qualitative data was collected during energy mapping discussions with additional 20 households. Among them, 6 were female registered system owners and 14 were male. Average age was 39 years, and the distance from the grid was on average 10 minutes, with 50% of households located 'under the grid' (i.e. in the immediate proximity to the grid). 2 were connected to the grid network.

Survey responses were analysed in SPSS and NVivo as some of the questions were open-ended and captured qualitative insights, whereas the analysis of the energy mapping discussions was carried out in NVivo and with the use of the general inductive approach for theory building, which uses readings of raw data to extract themes, concepts and models through the interpretation of that data by the researcher (Thomas, 2006:238).

2.1 Study location and context

This study focused on Rwanda as it has been one of the most vibrant off-grid SHS markets in East Africa in the recent years and one of the primary markets for the SHS provider. With numerous barriers to extending energy access, including very low average incomes, challenging landscape and remoteness of households, the country has turned to off-grid solutions as viable options for electrifying those without access and with poor prospects of connecting to the grid network in the near future. The Government of Rwanda have shown clear and strong support for the off-grid solar sector by including it in its Economic Development and Poverty Reduction Strategy II, as well as its Rural Electrification Strategy which specifically involves SHSs for scaling up energy access. With increasing but still relatively low levels of access at approximately 40.5% of the total population (with approx. 11% off-grid) (in 2017) (RDB, 2018), the plan is to increase it to 100% by end of 2024, with at least 48% off-grid electrification (GoR, 2016). The Government have also partnered with a number of companies offering SHSs and other off-grid solar solutions to achieve the set goals. Private providers have been encouraged by favourable conditions to grow their businesses and support from the Government,

[6] Poverty levels were measured using the Progress out of Poverty Index (PPI) for Rwanda (2005 PPP, confidence level 95% and confidence interval 7%). PPI data for energy mapping participants were not collected.

including through Rural Electrification Campaign aiming to spread awareness of off-grid solar systems (GoR, 2016).

Seeing how off-grid solar is going to play an important role in the country's socio-economic development, and the expectations that may be placed on the sector and the off-grid solutions it offers, it is critical to gather evidence for the changes observed among the adopters so far, and get a better understanding of how energy is used, how that use changes over time, and whether households indeed climb the solar energy ladder.

3. Results and Discussion

We focus on energy consumption and practices relying on access to electricity services (e.g. using light, charging mobile phones) which are supported by the SHS systems. Tables 1 and 2 below demonstrate what kinds of system packages (under System Name), as available from the provider, and appliances that come with them are present in our sample. Lights are the one appliance owned by everyone with other appliances distributed in different numbers across system packages and the three Groups.

Group	System Name	Cost (per month)	Frequency	Frequency (SMART Solar)	Appliances	Number (cumulative)	Number (cumulative SMART Solar)
Group 1 >1year	BB Lights	RWF6000	64	51	LED bulbs	197	151
	BB Super Lights	RWF11500	7	3	Torch light	30	16
	BB TV	RWF14500	16	10	Phone charger	84	64
	Total		**87**	**64**	Radio	72	53
					TV	14	10
Group 2 6-12months	BB Lights	RWF6000	61	55	LED bulbs	211	195
	BB Super Lights	RWF11500	6	5	Torch light	33	32
	BB TV	RWF14500	22	22	Phone charger	82	76
	Aguka	RWF5850	1	1	Radio	68	63
	Total		**90**	**83**	TV	23	23
Group 3 <6months	BB Lights	RWF6000	12	11	LED bulbs	236	190
	BB Super Lights	RWF11500	2	2	Torch light	6	6
	BB TV	RWF14500	2	2	Phone charger	82	66
	Ikaze	RWF3900	42	32	Radio	25	20
	Aguka	RWF5850	29	23	TV	3	3
	Total		**87**	**70**			
TOTAL			**264**[7]	**217**			

Table 1. Numbers of various system packages among study participants in each Group, including the default price for each system package (in Rwandan Francs - RWF), which can vary depending if extra appliances have been added to the original package.

[7] In the sample of 265 respondents, one respondent failed to complete the self-reported energy usage matrix hence the total sample here is 264.

System Name	LED Bulbs (1.2W)	Torch Light (4.2W)	Phone Charger (5W)	Radio (5W)	TV (7-9W)
BB Lights	2	0	1	0*	0
BB Super Lights	3	2	1	1	0
BB TV	3	1	1	1	1
Ikaze	2*	0*	1	0*	0
Aguka	4*	0*	1	0*	0*

*These appliances could be added to the initial set packages at the time of purchase or after a period of time. Additional light bulbs could also be added.

Table 2. System packages and appliances included in each of them, and their capacity (in Watts (W)). There are variations among customers, among Ikaze and Aguka owners as there was more flexibility in choosing appliances at the time of purchase and as upgrades. See section 4.1 for details of the change in available packages as introduced by the provider.

In the following sections, we will first look at a snapshot of how energy is used in the household by examining the appliances and the time(s) of their use throughout the day as self-reported by survey respondents and the data collected from the systems through remote monitoring. We also compare the usage among Group 1, 2 and 3 to check for any differences in usage patterns and levels depending on how long the systems have been in use for, which we assume to be one of the indicators of whether or not users climb the solar energy ladder by using more energy the longer they use their systems for. We then explore the question of productive uses of SHSs, which is another indicator pointing to whether or not access to electricity services boosts household economics, as is often expected through the provision of electricity access and has been tested for adopters of SHSs before (e.g. Rahman & Ahmad, 2013). Furthermore, we examine adoption rates of new appliances to challenge the solar energy ladder perspective, while at the same time corroborate the theory that practice change occurs as a result of getting access to additional appliances and thus new energy services. The latter part of it is explored by looking at examples of different SHS appliances to discuss how their use influences practices, causing their emergence, disappearance and/or change.

3.1 Energy consumption: to climb or not to climb the ladder?

Our working assumption derived from the energy ladder concept is that as households gain access to more appliances and with the passing of time they will start using more energy and therefore require ever higher capacity of the systems in order to satisfy the growing use and needs. We test this assumption by looking at the three Groups of customers who own different system packages offered by the provider, and within them different sets of appliances, subsequently looking at their energy use patterns.

Figure 2 below demonstrates the collective number of different appliances owned by customers in all three Groups (based on Table 1) and Figure 3 provides a cumulative number of all appliances across the same three Groups:

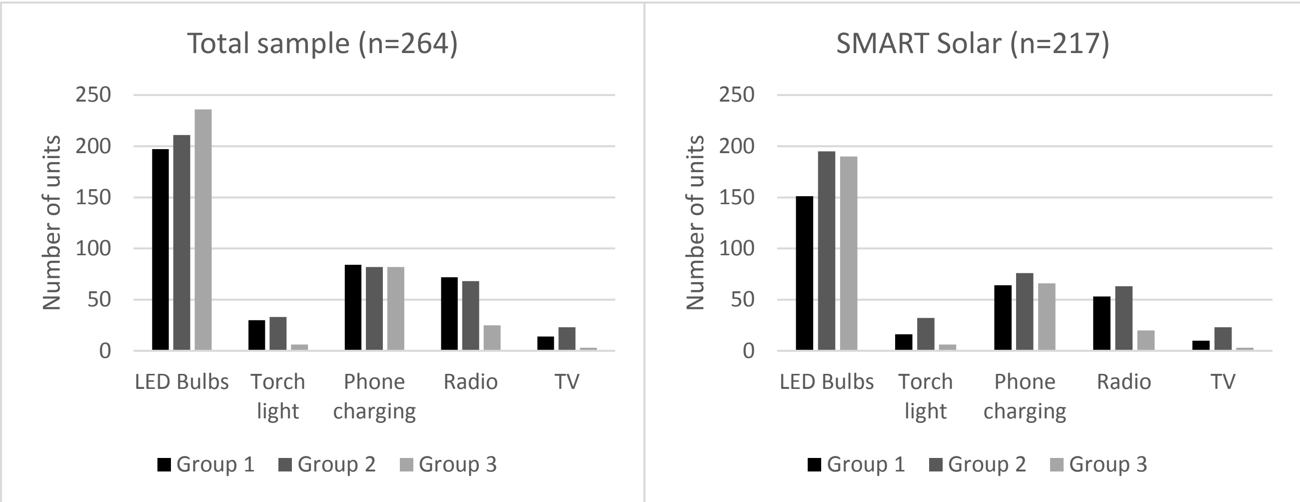


Figure 2. The number of different appliances owned in Group 1, 2 and 3 against the average number of individual appliances owned for the entire sample for both the total sample and the SMART Solar data sample.

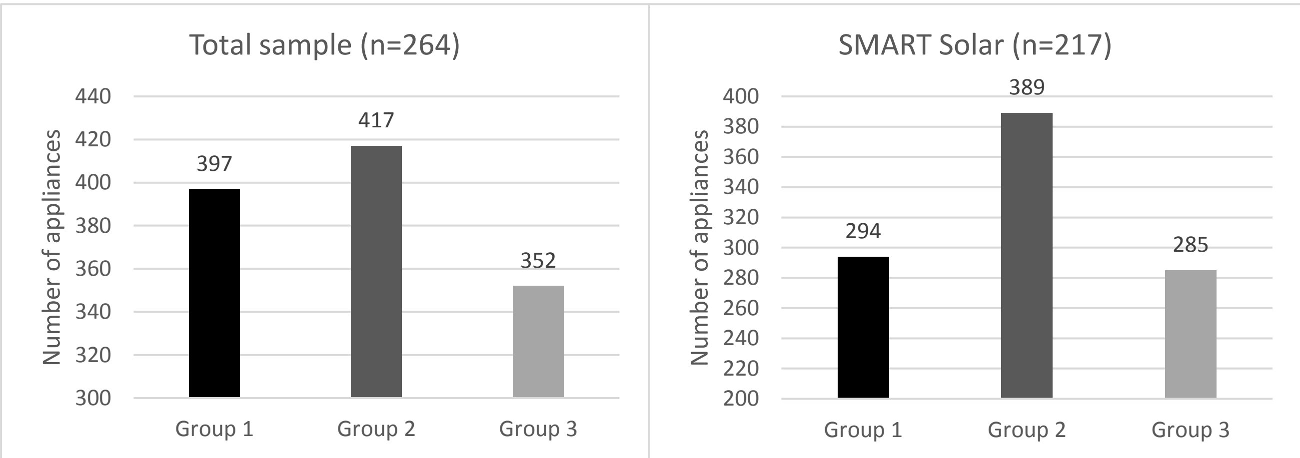


Figure 3. Cumulative number of all appliances owned in Group 1, 2 and 3 for the total sample and the SMART Solar data sample.

As shown in the above figures, Group 3 has the lowest overall ownership of appliances, albeit more pronounced in the total sample than in the SMART Solar sample where the cumulative number of appliances in Group 3 is comparable to that in Group 1, with fewest torch lights (portable lights), radios and TVs. The only appliance which Group 3 exceeds the other two groups at is the number of LED bulbs (although that is not the case in the SMART Solar sample where the cumulative number of LED bulbs is just below that of Group 2).

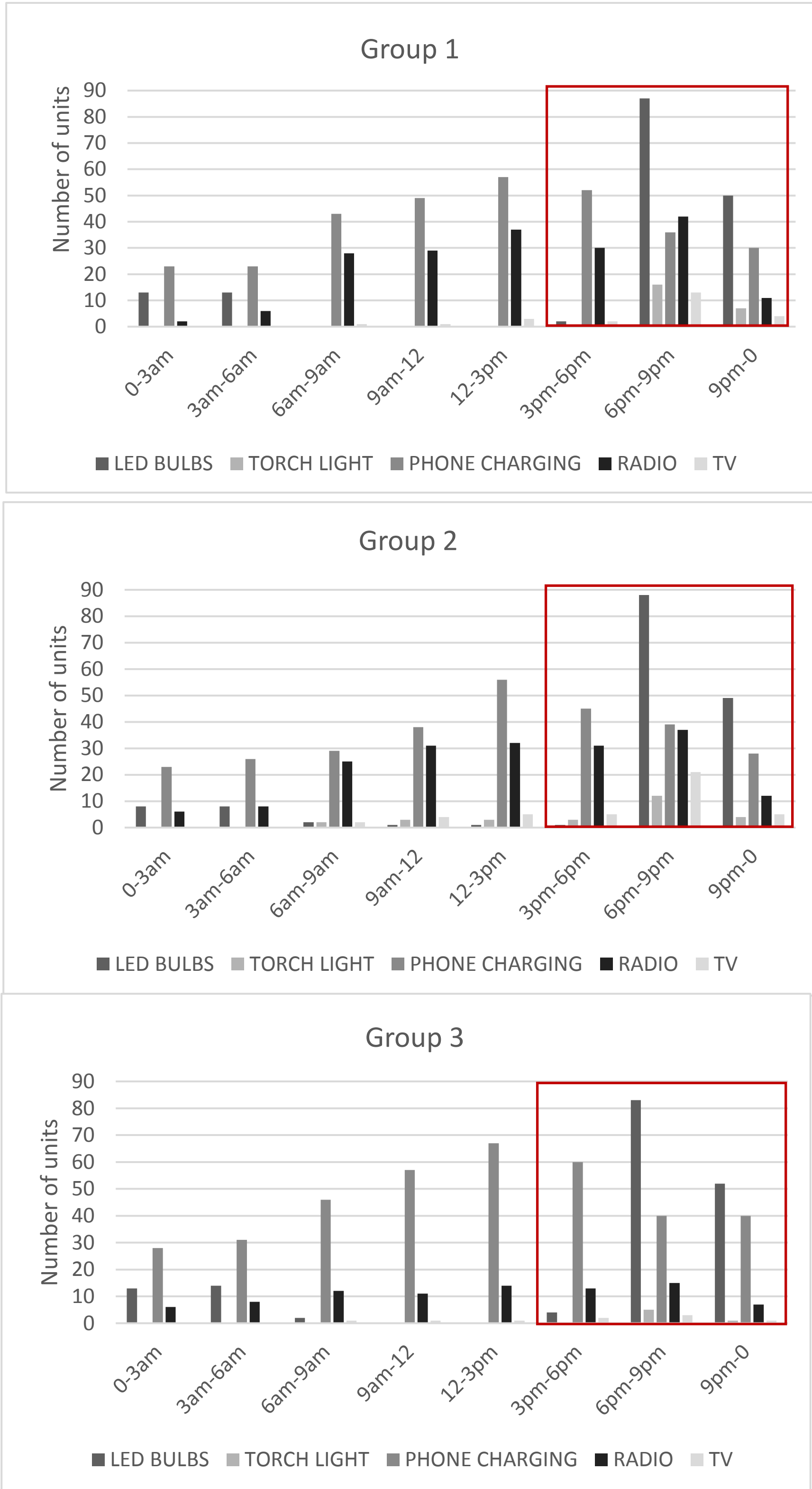


Figure 4. Self-reported use of system appliances in Groups 1, 2 & 3. Graphs show the cumulative number of appliances among survey respondents (n=264) used at different times throughout the day and night. Afternoons and evenings are times of highest diversification of use.

The self-reported system use in Figure 4 shows how energy consumption is distributed across the day among the three Groups and offers insight into which appliances are used at what times (on an average day). Lights use is the highest in evening times and at night, TVs are used predominantly in the evenings, mobile phone charging throughout the day, evening and night, with other appliances varying throughout the day. Afternoon and evening times show the greatest diversity of appliances in use, clearly demonstrating the more limited range of appliances in Group 3. Households in Group 1 report an overall higher level of usage than those in Groups 2 and 3, however, the use of mobile phone charging is consistently highest in Group 3.

Group 3 own, on average, fewer appliances than those who purchased their SHSs earlier. The six month threshold in this group (i.e. less than six months since purchasing the system) coincides with the change in packages on offer that was introduced by the provider in Rwanda in the first quarter of 2016 and moved away from BB Lights, BB Super Lights and BB TV to Ikaze and Aguka which included fewer appliances by default and required customers to actively add extra appliances (e.g. a radio, more lights or a TV) for a bigger package, automatically increasing the price from the basic to an appropriately higher one (depending on what appliances were added) (see Table 1 and Table 2). This could have contributed to more hesitation to purchase systems with more appliances as the offer price would no longer hold, i.e. the price the customers would initially see would not be the one they would have to pay. In the case of previous packages, the three different system offerings were sold at set prices for each one, depending on the appliances, and the customer would pay the price of the package they would initially be presented with, e.g. BB TV would always be RWF14500 and BB Lights would always be RWF6000 per month. As rural, off-grid households are very price sensitive, often having irregular, seasonal incomes, the lower the price of a service which can satisfy the basic needs, the higher the likelihood they will decide to purchase it. Any extras, which in the case of SHSs are the additional appliances, are seen as optional and often aspirational rather than critical, and can typically be afforded by more wealthy customers.

Despite having fewer appliances (on average), Group 3 have been found to consistently use, on average, more power than the other two Groups (see Figure 5 below).

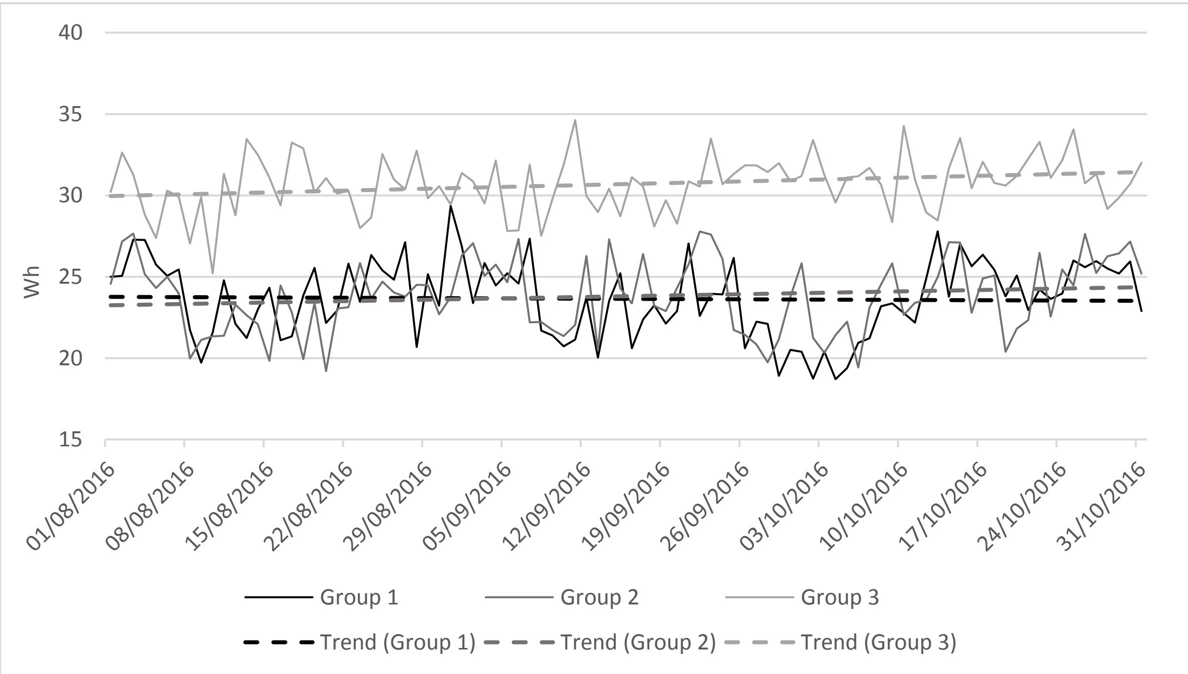


Figure 5. Daily energy use (in Wh) per Group across a three-month period between August and October (2016) as shown in SMART Solar data collected via remote monitoring of the systems (n=217).

Considering the lower number of appliances in Group 3, and particularly given the very low number of TV sets which are the most energy-demanding, the obvious assumption according to the energy ladder concept would be that fewer appliances mean less power used. Yet Group 3 maximises the use of available energy with the basic appliances owned, using them more than in the case of the other two Groups. The most notable one is mobile phone charging and, to a lesser extent, lights, which households in Group 3 report to use for income generation, making an average of RWF70 per week, as compared to Group 2 at RWF37 per week and Group 1 at RWF54.5 per week. Group 3 also pay the least for their system per month at an average of RWF5380 (median RWF5850) as compared to an average of RWF7976 (median RWF6000) in Group 2 and an average of RWF7858 (median RWF6000) in Group 1, making it the best value for money use in Group 3. Just like the trend of consuming more power, the trend of using the SHSs for income generation appears to be upward from Group 1 to Group 3, despite the reverse trend of decreasing numbers of appliances owned from Group 1 to Group 3.

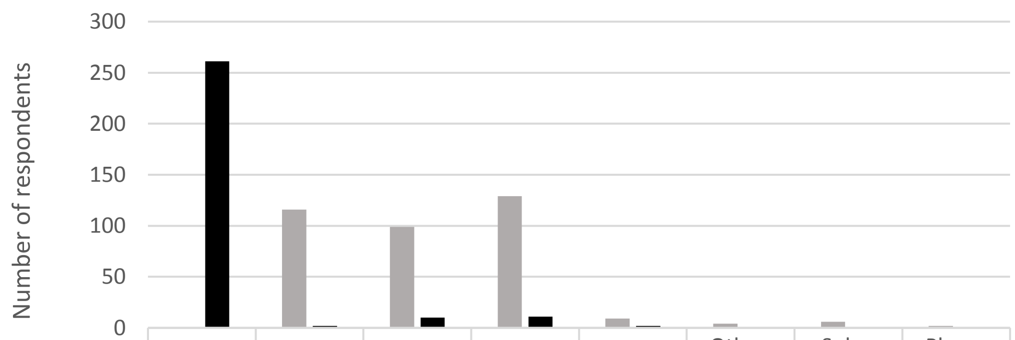
Despite using the most power, when asked if they ever run out of energy from their systems, 56.3% respondents in Group 3 answered no, compared to 62.5% in Group 1 and 45.6% in Group 2. This disproves the assumption that the more power is used the more likely it is to run out of it, and that the more appliances are used with the system the more likely it is to run out of power. This lack of clear relationship between the amount of energy used and a) the number of appliances owned, b) the period of time since system adoption, and c) the need for more power and therefore more system capacity, corroborates the fact that energy is used in a dynamic way, rather than gradually increasing, which the hypothetical solar energy ladder concept would indicate. In terms of household economics, it is not the diversity of appliances that dictate income generation, but rather the maximisation of use and perceived value for money of the available ones. Therefore, more appliances in the household do not automatically increase productive uses and income generation. Overall, productive use applications among SHS users have been observed to be very low, as are incomes generated from those applications, with a majority of adopters using the systems for in-household purposes only.

There is a number of insights which stem from the above. Firstly, energy consumption does not increase in a linear manner depending on the number of appliances owned. Rather, SHS adopters use the systems more dynamically, with some maximising the use of available power with only a few appliances, and others using their systems in a more conservative way while having more available appliances. Those who use the systems for income generation tend to use more power, on average, however, that is independent of the number of appliances owned, as has been seen in the case of Group 3. Secondly, those with more appliances are not automatically more likely to use their systems for income generation, which is proven by the case of Group 1. Thirdly, the overall appliance acquisition is low and majority of customers do not go beyond the basic ones which include lights, phone chargers and, to a lesser extent, radios. TVs and other appliances are rare as they come at a considerably higher cost, thus remaining predominantly aspirational. From among the n=265, only one customer belonging to Group 3 upgraded the system by adding additional appliances after a year since data collection (i.e. between September 2016 and September 2017). Regardless of how long they had owned the system for, there has been no upward movement on the solar energy ladder in the sense of additional appliance adoption seen among the study participants.

3.2 SHS and social practices

In the case of SHSs, where energy is collected during the day and stored in a battery with a limited capacity, energy can be used, to an extent, throughout the day and in the evening/at night until the battery drains. The practices associated with energy have to therefore be arranged according to the availability of energy from the system, which in Shove's terms is the *procedures* of energy use. In this way, the question is not about rearranging practices to best fit the low vs high demand times (as is the need in places with unlimited, reliable electricity where shifting practices are intended for sustainability transitions (e.g. Smale et al., 2017) but to fit them around times when energy from the system is available, which is also demonstrated in Figure 4). They also depend on the available appliances which constitute the *material objects* of energy use. Training and knowledge of how to most efficiently use the system, or the *know-how* of energy use, can help and such training is provided to customers at the time of system installation (which is also the case among other similar providers). However, as practices emerge and change over time, so does the system *know-how*. Customers become more familiar and comfortable utilising the system over time and with use experience, although that adaptation happens quickly and no sophisticated technical knowledge is required. Across all three Groups, 96.6% said they were able to use the system with ease.

The most common reason for purchasing a SHS among survey respondents was to have light (43.8% of respondents). Light is used in the morning while preparing for work and school and after sunset. In the evening, it enables the performance of various activities around the house, including but not limited to, food preparation and having meals, washing (clothes, dishes, oneself), studying, reading, socialising (with family, friends or neighbours), nursing babies, ensuring security (whether indoors or outdoors), doing work or preparing for work for the following day, playing around the house and other forms of entertainment. Activities which used to be performed in the morning or during the day, while light was available, e.g. washing dishes, have now shifted to the evening. An overall re-scheduling of daily routines and chores has been observed, mostly due to the availability of a reliable lighting source in the evening, which has implications for the *schedules*, as depicted by SPT. In addition to the temporal shift of some practices, there has also been a shift in space, for example for children who have gained the ability to play around the lit up house instead of having to wander off to seek lit up environments or household members gaining access to entertainment at home rather than outside. Light used to be available before the adoption of a SHS, however, it was either unreliable or produced smoke which would prevent or limit the performance of some activities, mainly due to discomfort. A significant change in lighting sources used in the household is demonstrated in Table 3 below. This change supports the energy ladder concept in that there is a noticeable elimination of traditional lighting fuels which are replaced by a SHS. Only 6 respondents had used a solar lantern before adopting a SHS, which is a relatively small number to support the solar energy upward movement concept from smaller to bigger off-grid solar solutions.



	SHS	Kerosene	Candles	Batteries	Grid	Other SHS	Solar lantern	Phone light
Lighting in the Household Prior to current SHS	0	116	99	129	9	4	6	2
Lighting in the Household Post current SHS adoption	261	2	10	11	2	0	0	0

Table 3. Lighting sources used in the sampled households before and after adopting the current SHS (n=265).

However, the same movement as in the case of lighting sources is not observed in the case of cooking, not currently supported by SHSs, which implies that the ability to access a modern source of electricity does not go hand in hand with moving on to modern cooking fuels as well. Table 4 below shows the common cooking fuels in use.

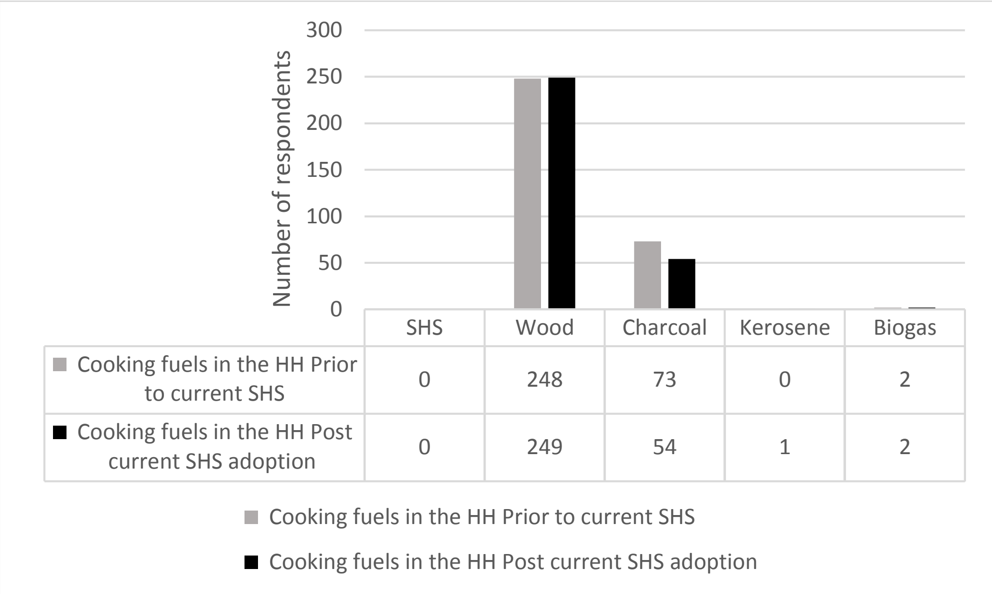


Table 4. Cooking fuels used in the households before and after SHS adoption (n=265).

A slight drop is noticeable in the use of charcoal but no other significant shifts are present between the before and after scenarios. Firewood is most commonly utilised which results from its availability, accessibility and low to no cost when compared to alternatives. The presence of different cooking fuels in addition to the lighting sources including a SHS support the energy stacking practice, where various energy sources are used at the same time, for the same or for different purposes (Masera et al., 2000; Baiyegunhi & Hassan, 2014).

The change in lighting sources from kerosene, candles and batteries to SHS supports the energy ladder concept (van der Plas & Hankins, 1998) as users move from an inferior source to a superior one when it becomes available. However, a number of households in our sample have adopted a SHS after having access to the grid network, which suggests a step down the energy ladder. The motivations for that were two-fold among the 9 respondents: firstly, the grid connection was unreliable and with frequent blackouts they would often be left with no electricity and therefore no light in the house, which would force them to resort to candles, kerosene or torches to light their houses at night; secondly, with regular power surges, the grid connection is perceived as dangerous due to the risk of electrocution, which was of particular concern among study participants with children. 2 out of 9 respondents continued to use the grid in conjunction with the SHS as a complementary source.

Irrespective of the dichotomy of upward and downward movements, the evidence points to energy stacking behaviour apparent in the utilisation of multiple cooking fuels and lighting sources, whether at the same time (e.g. grid and SHS) or at different times (e.g. torches, candles or kerosene on occasions when SHS does not function or grid black out takes place). Jointly, the complex energy use conditions support the theory that even as households gain access to more modern energy sources, multiple fuels remain in use.

Having a modern and reliable source of lighting creates an overall feeling of improved well-being and safety (Parikh et al., 2012; Hirmer & Cruickshank, 2014; Harrison & Adams, 2017), both in respect to decreased fire hazard from candles or kerosene lamps, potential electrocution from the grid system (among the 9 households with grid connections prior to adopting a SHS) and outdoor and indoor safety at night, allowing more ease of moving around one's property and to deter external hazards such as thieves or wild animals. Fire hazard and smoke reduction might, however, be compromised by the continued presence of polluting sources used for cooking (whether firewood or charcoal) in the household.

Reliable and clean lighting is the most basic service that comes with a SHS and is available to all customers. It is responsible for a considerable proportion of practice changes. However, practices emerge and are rearranged not only as a result of having access to a cleaner, more reliable and safer source of lighting than prior to system adoption, but also due to the discontinuation or substitution of pre-existing practices (Lipschutz, 2015). A notable example is the need to go out to purchase light sources (candles, kerosene or batteries for torches). Time is saved as those trips no longer have to be made which creates time for other practices to emerge or for the rearrangement of existing ones. As one practice disappears- the going out to make the purchase, another one emerges- the making of the monthly payment for the system. The system payment, however, can be done via a mobile phone for customers using mobile money (minimal time required) or at a local mobile money agent or a bank, which also requires a certain amount of time to complete but only takes place once a month. As majority of adopters move towards the ever more prevalent mobile money technology (UNCTAD, 2017), this need will eventually be eliminated altogether.

Given the ubiquity of mobile phones in Rwanda, and many other Sub-Saharan African countries (David et al., 2015), the need to charge them exists for the majority of those who adopt SHSs. In our survey and workshops all participants owned at least one mobile phone per household, and frequently more. Next to having light, being able to charge mobile phones is an important motivation for purchasing the system. 48.3% of survey respondents mentioned it as one of the key motivations for purchase. Having a SHS moves the practice of charging phones externally at a shop or a charging station (at a relatively high cost of RWF50-100 per charge) and brings it into the home, allowing for more flexibility of when to do it and eliminating the need to take a trip out to have it charged, similarly as in the case of purchasing lighting fuels. Both constitute another spatio-temporal practice change. They also reduces the risk and inconvenience of running out of a lighting fuel or phone battery.

As discussed in earlier sections, having access to a source capable of charging phones, some customers have started charging them for others (e.g. neighbours or friends). Out of the 73.2% of respondents who said they were doing it for others (mainly family, friends, and neighbours), 11.2% said they were offering it at a charge. Majority would not charge anything and a few said they would charge but only sometimes. In addition to the new practice (in-household mobile phone charging) triggering income making opportunities, practices of other individuals or groups have been impacted as well by changing the location where they have their phones charged.

Although most practices are routinised and performed without conscious decisions being made each time prior to performing them, Gram-Hanssen (2014) argues that conscious decision can also influence practices, of which the above could be one example. What is distinctly different in the case of low-income households relying on off-grid electrification is that the coming together of what Shove (2017) refers to as "devices, infrastructures and resources" might be limited to fewer devices or resources as a SHS has a capped capacity (depending on the panel and battery size) and typically there are only basic appliances that come with it, such as lights, radios, phone charging ports, with appliances such as TVs, fans, shavers and others being rare, and not always readily available for additional purchase, depending on the range of appliances offered by any given provider whose services the users are subscribed to.

As follows from the above, energy consumption is a non-linear process which does not consist of a single practice but rather of several different practices related to one another both vertically and horizontally, with changes in one practice affecting other related practices (Gram-Hanssen, 2011), also among users of SHSs as demonstrated in this study. Each appliance carries with it a potential to impact on a variety of existing practices and the creation of new ones. Mobile phone charging, for example, can only be performed if phone chargers are available, while TV entertainment is only available to those who own a TV or have an easy access to one. As much as the practices that emerge, change and contract as a result of the shift towards a modern energy source depend on the appliances that are available, making up the *material objects* of energy use, it is the intensity of use, or the *procedures*, rather than the number or diversity of appliances that dictates the amount of energy used in the household, as has been shown in section 4.1. The maximum value for money, in our study, is achieved in the Group with the lowest number of appliances and the highest average income generation from the most common productive use of the appliances and practices changes- in-household phone charging. This could have implications for the off-grid energy sector to gain further insights into what practices (whether emerging or changing) drive the highest energy use and where income generation falls in the landscape of off-grid energy transitions. It should also be acknowledged that although the increase in appliance ownership does not immediately or automatically boost the economic well-being of households relying on SHSs for energy access, it does create more opportunities for practice shifts which have the potential to improve the overall well-being of household members, changing and expanding the *meanings* of having access to energy. It offer new services beyond the basic ones, thus fulfilling individuals' and household other existing needs and aspirations and allowing them to climb up the 'energy services ladder' (Sovacool, 2011). This could also be seen as a climb up the 'development ladder' or 'aspirations ladder', which is linked to the climb up the solar energy ladder in that it requires additional appliances beyond the basic ones, which are the most prevalent among SHS users.

4. Conclusions and recommendations

The contribution of this study lies in adding to the limited body of knowledge on the sociology of energy behaviour among rural off-grid solar adopters in the developing context. We have hereby examined the energy consumption patterns and the shift in practices as a result of gaining access to improved energy services among SHSs adopters in Rwanda through the application of the SPT and the energy and solar energy ladder framework. Energy consumption is dynamic and driven by dynamically changing practices which shift in terms of their spatio-temporality: they are moved both in time and space. Practices change, are substituted or eliminated, while new ones are created, impacting on the *know-how* and *meaning* related to energy consumption among SHS users. Value is created through new procedures made possible by the available energy services. In line with Faller (2015), we find value creation in practices: "from household oriented practices to practices of economic production", although that shift does not correspond with higher numbers of available appliances or longer periods of system use, as is assumed in the adopted concept of a solar energy ladder. Energy consumption has been shown to be used dynamically and independently of the number of appliances owned. The hypothesis that energy consumption increases over time has also been disproved through the analysis of actual power consumption data. Further research on the drivers of energy use and, in particular, of income generating activities among different groups of SHSs adopters with diverse sets of appliances and characteristics, and distinct context (e.g. urban, peri-urban or rural) is required to inform strategies on estimating demand and tailoring the product and the service according to those drivers.

Lighting and mobile phone charging are the dominant practices driving energy consumption among SHSs adopters, with only few other appliances currently in use, and with a low new appliance acquisition over time. Historically, as pointed out by Gram-Hanssen (2011), that was the case in other countries as well (e.g. Denmark and its grid network expansion), even as efforts were being made to drive higher levels of consumption and promote activities requiring additional appliances. Multiple energy sources are in use at the same time, including cooking fuels which do not undergo any significant transformation post adoption of a SHS, clearly pointing to energy stacking and to a more complex movement on the hypothetical energy ladder. Understanding the context of how energy is practiced (Lipschutz, 2015) provides a valuable insight into the path energy transitions are taking in off-grid, rural communities adopting solutions such as SHS to gain access to energy services. “Practicing actors relate these contexts to physical-material components and thereby create spaces of transitions” (Faller, 2015:93) which do not necessarily follow the energy or solar energy ladder trajectory and prove to be more complex and dynamic. Insights into the multi-faceted nature of energy access and the multiplicity of fuel use can prove invaluable in ensuring appropriate socio-technical and policy strategies for future efforts in providing adequate energy services.

The value of our analyses lies in the utilisation of both consumption and survey data, and rich qualitative data which together depict the complexity and the dynamic nature of energy use among SHS users. The currently scarcely available consumption data will prove invaluable in modelling energy consumption, with technologies of remote monitoring of SHS complimenting studies such as this one and having the potential to significantly improve and adapt energy services to users’ needs (Bisaga et al., 2017). With the rapidly expanding market for off-grid solar energy (Dalberg Advisors & Lighting Global, 2018) the volume of new consumers interacting with energy systems such as SHSs or similar will continue to grow. Given the changing trends in energy access provision from the traditional grid extensions to decentralised solutions, which have been shown to offer a better socio-economic value (Lenz et al., 2017; Lee et al., 2017), more research is needed to fill in the still many existing gaps on how energy is used and what trajectory the new energy transitions are taking among off-grid consumers. Better understanding the different ways in which even basic appliances are used to create and maximise value can be critical for both private providers and practitioners working in this sector whether for the design of appropriate business models, energy efficient appliances or end-user guidelines. This, in turn, can further help consumers who might aspire to own more appliances (whether more of the ones they already have or more diverse ones) to access them by making them more affordable and appropriate in terms of design and specifications (e.g. efficiency, compatibility, etc.). As postulated by Tang & Bhamra (2008) in the context of sustainability transitions, so in the off-grid energy transitions product design should play a salient role in shaping consumption.

The dynamic energy consumption trends demonstrated in this paper and prioritisation of basic appliances, as well as relatively low to no upward movement on the solar energy ladder pose a question of potential taxation and subsidy challenges which, if revisited, could spark higher levels of adoption and open up the market of appliances to off-grid and grid users alike, as they have also been found to demonstrate low levels of appliance adoption post electrification (Lee et al., 2016; Lee et al., 2017). This study also calls for putting in place mechanisms for community engagement and business model design which can further explore and incorporate such complex, non-linear patterns of energy use. Practitioners – consumer facing models will be needed to support new types of interactions with energy systems. Such models and mechanisms (see e.g. Bisaga et al., 2018 (in press)) can assist policy makers to engage with users and user communities to better gauge and help predict future demand, moving away from the expectations of trajectories depicted by the energy ladder which has been challenged before and, as this study has argued and corroborated, is more complex and dynamic than traditionally assumed. Such learnings can be utilised for the improvement of services and customer retention, marketing of products and services, as well as finding new ways of enabling income generation among the growing number of SHS adopters. While the social aspects of energy use should not be neglected and the benefits of access should not be denied, alternative ways of sparking further socio-economic development of newly electrified households will have to be sought by all stakeholders working towards universal electrification and thus human development.

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