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Keywords : Energy transition; Off-grid system; Sub-Saharan Africa; Social Shaping of Technology; Gender; Disruptive innovation

JEL Classification D1, N37, P28, P46, Q4

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Socially inclusive renewable energy transition in sub-Saharan Africa: A social shaping of technology analysis of appliance uptake in Rwanda

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Abstract

Rural off-grid renewable energy solutions often fail due to uncertainties in household energy demand, insufficient community engagement, inappropriate financial models, policy inconsistency and lack of political will. Social shaping of technology (SST) of specific household electric appliances provides a critical lens of understanding the involved socio-technical drivers behind these constraints. This study employs an SST lens to investigate appliance uptake drivers in Rwanda using the EICV5 micro dataset, such that these drivers can aid in policy design of a socially inclusive renewable energy transition. The methodology includes a systemic and epistemological review of current literature on the drivers of appliance uptake in the Global South. These drivers were then analysed using binary logistic regression on 14,580 households. Results show that appliance uptake is highly gendered in Rwanda and the type of appliance determines its diffusion across the welfare categories, commonly referred as to Ubudehe categories. Regression results show that mobile phones, radios and TV-sets have a higher likelihood of ownership than welfare appliances (refrigerator and laundry machine) by low-income households. There is also a high likelihood of uptake of power stabilisers in urban areas, indicating poor power quality. Policy implications were drawn using the lens of disruptive innovation.

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1. Introduction

Gendered perceptions, preferences, ownership and benefits from electrical appliances for United Nations Sustainable Development Goals (SDG) 1 (poverty reduction), 7 (affordable and clean energy provisioning) and 17 (partnerships for the goals) remain an under-researched area in the off-grid and rural context of the Global South. Despite advances in technology, people in rural areas still use crude traditional stoves with biomass-based fuel for cooking and kerosene for lighting (Ouedraogo, 2019). It has significant adverse health and well-being implications on the national burden of diseases and is extensively acknowledged in the literature (Fullerton, Bruce, & Gordon, 2008). It remains the case for 2.8 billion people globally (Bruce et al., 2015). In addition to reliance on traditional cookstoves, uptake of electrical appliances for household tasks, income generation and service-delivery continue to remain low. With the contemporary regime of micro-girds and renewable energy transition, it is crucial to understand the demand-side response of renewable technology innovations in resource-constrained setting (like rural areas) for designing "good" energy policy (Ozawa, Chaplin, Pollitt, Reiner, & Warde, 2019).

Higher uptake of electrical appliance is central to the achievement of SDGs and improved livelihood opportunities in poverty (Chaudhury & Tyagi, 2018). This study takes a two-step approach to understand the drivers of appliance uptake in African rural communities. First, a systematic literature review is conducted to identify factors critical in influencing appliance uptake in resource-constrained settings in the context of Global South and sub-Saharan Africa. Second, the performance of local communities in appliance uptake is investigated in rural Rwandan using binary logistic regression on Integrated Household Living Conditions (EICV5) micro dataset. In doing so, this study seeks to understand the process of technology diffusion in rural Africa and establish vital policy indicators for the socially inclusive energy transition. Social Shaping of Technology (SST) framework is used to visualise and integrate the social inclusiveness, community and gendered appliance uptake (MacKenzie & Wajcman, 1985). SST explores how the design and implementation of technology are patterned by a range of 'social' and 'economic' factors as well as narrowly 'technical' considerations (Williams & Edge, 1996). This approach aided us in understanding the complex relationships between technology innovation diffusion of renewables in rural Rwanda and the social factors influencing the process of diffusion. The key indicators of SST are derived through an in-depth epistemological review of appliance ownership, gender dynamics, technology change and socio-cultural elements.

Globally, technological innovation is happening in a very fast and the knowledge of its diffusion at a local level is vital to understand the process of 'just' energy transition. At a provincial level, energy transitions are complicated because, despite new technological innovations and solutions, traditional appliances continue to co-exist with electrical appliances, so there has been the use of multiple energy sources. A significant corpus of literature on energy transition in Africa had been focussing on the dualities of energy use and storage in rural and low-income communities through the lens of 'energy stacking' (Choumert-Nkolo, Combes Motel, & Le Roux, 2019; Ouedraogo, 2019). However, there is a significant literature-gap in examining the implications of the renewable energy transition and energy stacking behaviour, especially on the appliance uptake drivers.

The literature on the acceptance of renewable energy technologies had been concentrated on exploring the micro-grid technologies with the assumption that when such technologies are accepted, electrical appliances are also automatically accepted (Negro, Alkemade, & Hekkert, 2012a). This assumption influences the policy mechanisms to treat electrical appliances as a secondary component of renewable energy allocations, that has a snowballing effect on the distributional energy *injustice* of appliance ownership and renewable technology diffusion in rural and low-income communities in the Global South (Islar, Brogaard, & Lemberg-Pedersen, 2017; Negro, Alkemade, & Hekkert, 2012b). In this purview, we investigate the social shaping of technologies in Rwanda and derive pathways for social inclusivity in higher appliance uptake using the *theory of disruptive innovation* (after Christensen, 1997).

The primary research question of this study is, *how does specific appliance uptake is shaped by the social-technical drivers in resource-constrained setting?* To address this question, the following objectives are formed:

- To understand the drivers of household appliance ownership in rural Rwanda within the theoretical scope of SST.
- To examine the gendered influence on appliance uptake in Rwanda and establish vital indicators of the social inclusive energy transition.
- To derive higher appliance uptake pathways using the lens of disruptive innovation to support socially inclusive off-grid energy transition.

Addressing these objectives is not only crucial in answering the research question, but it also forwards a transformative local level appliance uptake approach which is consumptive-productive-service oriented. This derived approach outlines the novelty of this study, as a gendered and socio-technical narrative of consumptive-productive-service oriented appliance uptake would critically aid in designing appropriate policies for sustaining small and medium-sized rural enterprises, equitable allocation of appliance needs in resource-constrained setting (like in education, healthcare, administrative centres, entertainment and recreation), and for enabling distributive energy justice at a household level through appropriate energy services (lighting, cooking, heating, cooling, etc). The consumptive-productive-service oriented appliance uptake approach for the sustainable energy transition in rural and resource-constrained areas of Global South is illustrated in Fig 1.

The paper is structured as follows: section 1 defined the scope and conceptual framework of this study. Section 2 illustrates an in-depth literature review of appliance ownership drivers in low-income communities of Global South. This section also accentuates the need for gendered perspective in designing good energy policies at the community and grassroot-level. Additionally, this section also connects the critical links between gender and SST, and community influence on energy transition through a disruptive innovation perspective. Section 3 explains the overall methodology of this study and the use of EICV5 dataset of Rwanda for quantitative analysis using a binary logistic regression. Section 4 illustrates the results and links the critical implications of the results with the broader goals of the renewable energy transition. The conclusion and policy implications are presented in Section 5.

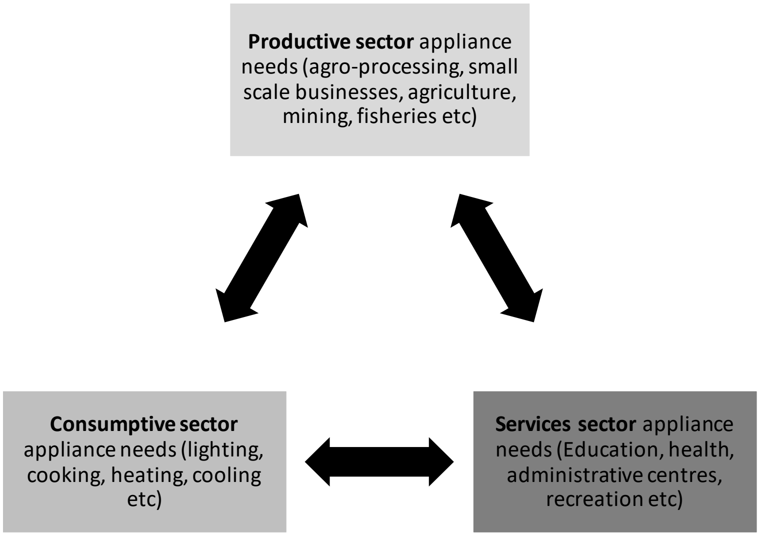


Fig 1. A conceptual local-level consumptive-productive-service sector-oriented appliance uptake approach for sustainable energy transition in rural areas

2. Literature review

2.1 Gendered implications of appliance uptake in sub-Saharan Africa and the Global South

Women's involvement in decision-making in domestic energy remains an under-researched area, especially in low-income communities. Understanding the importance of gender roles in energy consumption is crucial for sustainable energy policymaking at a household and neighbourhood scale, especially for rural mini-grid planning (Blodgett, Dauenhauer, Louie, & Kickham, 2017; Wang, Zhu, Ding, Zou, & Li, 2019). However, much of the present studies on gender and energy use is derived from empirical findings of the Global North. Few studies that lay the foundation of gendered influence on energy use and well-being in low-income communities show a strong relationship between the quality of the built environment, use of space and appliance ownership (Choumert-Nkolo et al., 2019; Johnson, Gerber, & Muhoza, 2019; Sunikka-Blank, Bardhan, & Haque, 2019), but do not report any critical variables that can help in prediction of energy demand in resource-constrained settings. In rural areas, this uncertainty associated with energy demand forecasting remains one of the critical barrier of mini-grid proliferation which adds financial risk to the investors (Blodgett et al., 2017).

Mini-grids and solar home systems (SHS) are crucial tools of off-grid electrification in remote rural and island communities. It has significant sustainable development and poverty alleviation implications in areas like sub-Saharan Africa, Asia and the Latin American countries. Despite the successes recorded in many countries of the Global South, the sub-Saharan African mini-grid electrification narrative portrays failure and limited success (Azimoh, Klintenberg, Mbohwa, & Wallin, 2017). The significant constraints against off-grid renewable energy-based electrification programs include lack of technical and managerial knowledge needed to run and maintain the systems, low-energy demand density, uncertainty of energy demand from households, disperse homestead, insufficient community engagement, inappropriate financial models, policy inconsistency and lack of political will (Adebayo, Sovacool, & Imperiale, 2013; Azimoh et al., 2017; Brent & Rogers, 2010; Cooper, 2007; IED, 2013; Julius, Olufemi, & Chuks, 2014; Taele, MokhutŠoane, & Hapazari, 2012). These challenges limit the socio-economical developmental impacts of the rural off-grid renewable energy transition programs.

However, electrification alone cannot solve all development problems, but access to electricity acts as a gateway to other forms of development assistance (D. F. Barnes, 2011). A recent study by Dhanaraj, Mahambare, & Munjal, (2018) in urban India have shown that improving household access to welfare appliances like refrigerator and washing machine to women living in low-income improves household welfare. The access to such welfare appliances improves the convenience of women that frees up their time from doing subsistence-based household chores (like cooking, cleaning and washing). This time is usually used in income-generating activities that contribute critically to the improvement of household welfare in low-income communities (Ramit Debnath, Bardhan, & Sunikka-Blank, 2019). It illustrates the importance of gendered capacity building in access to modern appliance uptake.

Additionally, in a broader sub-Saharan African study, Azimoh et al., (2017) have recommended that a gendered capacity building and technology transfer can substantially solve diffusion problems of renewable micro-grids in a rural areas. It can aid in better access to modern appliances in rural household. It, in turn, can foster ways for better financial models through electrification-gender-entrepreneurship nexus at local-level.

Gendered appliance uptake perspective at the local level is vital to establish the envisaged consumptive-productive-service link (see Fig 1). To establish this link, it is imperative to understand the gender-related choices and constraints of appliance uptake from a Social Shaping of Technology (SST) perspective (as mentioned in section 1). Literature shows that SST and gender-related factors are influential in determining appliance ownership in rural areas, as traditional appliances still co-exist with modern appliances even as the small-scale entrepreneurship in sub-Sharan Africa has increased (Sachu, Denver, Sajid, McMahon, & Rosenquist, 1999; Wüstenhagen, Wolsink, & Bürer, 2007). SST implicates in a triangulated manner such that socio-political acceptance, community acceptance and market acceptance remain in synchronisation (Wüstenhagen et al., 2007). In a similar context in India, Angelou & Bhatia, (2014) have reported that in both rural and urban households social processes and household structures determine appliance uptake, rather than sole income-related drivers as claimed by energy ladder concepts. Such drivers are called 'non-income' drivers of appliance ownership that are critical players in reshaping the demand of a particular appliance or technology (Ramit Debnath et al., 2019; Rao & Ummel, 2017; Sunikka-Blank et al., 2019; Wüstenhagen et al., 2007). Understanding these non-income drivers and the mechanisms of SST in low-income is essential for sustainable renewable micro-grid planning in rural areas as household moving out of poverty become the first purchaser of electrical appliances (Azimoh et al., 2017; Gertler, Shelef, Wolfram, & Fuchs, 2013; Ouedraogo, 2019).

2.2 Social shaping of technology in appliance uptake in the Global South

A recent growing body of literature exclusively focuses on the non-income drivers of appliance uptake in conjunction with the social shaping of technology (SST) theories. These studies are mostly focussed on the Global South and poverty alleviation context, as the consumption behaviour in these areas is highly complex, socio-culturally layered and have distinct rural-urban characteristics on technology choices (Azimoh et al., 2017; D. F. Barnes, 2011; D. Barnes & Sen, 2004; Choumert-Nkolo et al., 2019; Ramit Debnath et al., 2019; Kumar et al., 2019; Leach et al., 2012; Mastrucci, Byers, Pachauri, & Rao, 2019; Ouedraogo, 2019; Rao & Ummel, 2017; Shyu, 2014). The common thread between these studies is towards understanding the relationship between technology and social life in low-income and resource-constrained setting. As mentioned in section 2.1, a better understanding of technology and society can help in better off-grid renewable planning, execution and delivery, and is a must for realising UN SDG – 7. In this purview, we synthesise information on technology innovation and its influence on resource-constrained and rural societies of the Global South.

Wu, (2008) used an ethnographic approach to understand the complex relations between technology and social life in a Chinese rural setting and to explore the logic and dynamics of integrating new technology products into their everyday life. The author found that for quick technology adaptation in a rural setting, appropriation of technology is vital across the socio-cultural layers of rural areas. Wu (2008) also commented that for good energy policymaking, it is essential to understand everyday habitus and the gendered views on technology vis-à-vis household appliances. In a similar note, Bisaga & Parikh, (2018) have used a practice-based approach in examining the technology adaptation of solar home systems (SHS) in rural Rwanda. They found that social practice changes dramatically that, in turn, influences the social shaping of SHS. Due to this complex non-linear SST process, the energy consumption in a rural household does not increase linearly with time or with more appliance. Frederiks, Stenner, & Hobman, (2015) further expanded on the technology innovation and SST viewpoint in appliance uptake across economic classes to derive policy action points on more cost-effective and mass-scalable behavioural solutions to encourage renewable and sustainable energy use among consumers. In their in-depth review, the authors found that many studies reported that the consumers benefit from technological innovation in their daily practices, without which their well-being is affected (similar arguments made in Roberts, Hope, & Skelton, (2017)). Although these studies are from the Global North, the technology-well-being interdependencies remain valid in the Global South context as well (Juma & Yee-Cheong, 2005). Our study further expands the understanding of such interdependencies by assessing socio-technical drivers of appliance uptake in Rwanda, which can assist renewable-based microgrid providers to identify ways of improving innovations suitable for off-grid consumers.

A more in-depth literature search exhibited studies that have analysed the SST drivers of appliance uptake from an epistemological viewpoint. These studies are presented in Table 1, and we synthesised a flowchart of such SST weighed drivers of appliance uptake in poverty using the information presented in Table 1. The synthesised flow diagram is illustrated in Fig 2.

Table 1. Selected literature illustrating the influence of technology innovation and SST on appliance uptake in low-income and rural context of the Global South (source: Author)

References	**Epistemological arguments in relation to SST and technological innovation of appliance uptake**	**Methodology**
(Roberts et al., 2017)	Study found that 53% of adults reported regretting purchasing an electrical device at some point, and 23% regretted making such a purchase within the past year. The regretted consumption is triggered by the *pace of technology change* making the device obsolete. *[Note: this study is not from the Global South, but the implications are important for this study]*	National sample survey (n = 2000) across socio-economic classes, personal interviews and social practice theory of regretted consumption
(Ramit Debnath et al., 2019)	Change of household practices and built environment leading to shifting of energy intensive practices from outdoors to indoors in urban poverty of Mumbai. The respondents were *coming out of poverty*, technology change did not concern them, but rather they were *first-time buyers* of 'modern' appliance on a 'subsistence' basis.	Questionnaire survey of 1224 slum rehabilitation housing occupants using social practice theory. Analytical technique involved co-variance based structural equation modelling.
(Rao & Ummel, 2017)	Examined patterns of ownership of televisions, refrigerators and washing machines as welfare appliances. Authors found a hierarchy of preference in appliance uptake owing to physical quality of built environment and demographic characteristics. Race (colour) and religion was also found as a crucial *social force* shaping appliance ownership. Apart from this affordability, expenditure share and automobile ownership were also critical drivers.	Publicly available nationally representative household survey data from Brazil, India and South Africa. Analytical technique involved logit modelling and boosted regression tree.
(Bisaga & Parikh, 2018)	*Changing social practice* shape consumer behaviour towards adoption of solar home systems (SHS) in rural Rwanda. SHS acts as a technological force behind changing perception towards new technology adoption and energy stacking dynamics.	Empirical enquiry using social practice theory of 265 respondents.
(Mastrucci et al., 2019)	Social shaping of technology like air conditioning (AC) is important for addressing cooling needs in warming Global South. Solutions should be beyond improving AC efficiency and *focus on passive buildings and city design, innovative cooling technologies and parsimonious use of ACs.* Technology diffusion and innovative solutions are key to future cooling needs in the Global South.	Variable degree day (VDD) method on a global grid.
(McNeil & Letschert, 2005)	Importance of *local markets*, order of successive appliance purchases and corresponding income levels. Other parameters influencing appliance uptake are climate, degree of urbanisation, electrification rate.	Country specific interviews on appliance ownership and use patterns of appliances; Dataset from World Bank (Living Standards Measurement Study); national census datasets of Brazil, Mexico, Nicaragua, Panama, Peru and South Africa.
(Furaiji, Łatuszyńska, & Wawrzyniak, 2012)	Social factors (family, roles & status, age & life cycle stage); physical factors (occupation and economic status) and marketing mix (promotion and placement) were key drivers of *social shaping of consumer behaviour* towards appliance uptake.	Questionnaire survey of 200 households in Iraq, and structural equation modelling.
(Mohlakoana et al., 2019)	*More female participation* and energy stacking dominate small and medium enterprises of street food service (SFS) in	Mixed-method interview of 751 respondents.

	Senegal, South Africa and Rwanda. The need for affordable and accessible modern energy services in SFS shape the technology diffusion in these areas.	
(Blodgett et al., 2017)	Improving energy use surveys to improve accuracy of energy prediction in micro-grids for rural areas. It can aid in better technology diffusion and appliance uptake.	Surveyed and measured in eight mini-grids.
(Johnson et al., 2019)	The benefits of energy services and new technology *are not equally distributed* between men and women in rural energy transition due to *socio-cultural practices and norms*. It affects the *energy culture* that, in turn, determines the success of off-grid electrification program.	Qualitative examination of Mpanta solar mini grid in rural northern Zambia using energy culture perspective.
(Kennedy, Mahajan, & Urpelainen, 2019)	Electricity service quality determines the willingness-to-pay for grid-connected electricity bills (i.e., appliance use) in rural India. Indian policymakers can increase electricity prices in exchange for *improved services and better technology.*	ACCESS survey across 715 villages in six Indian states

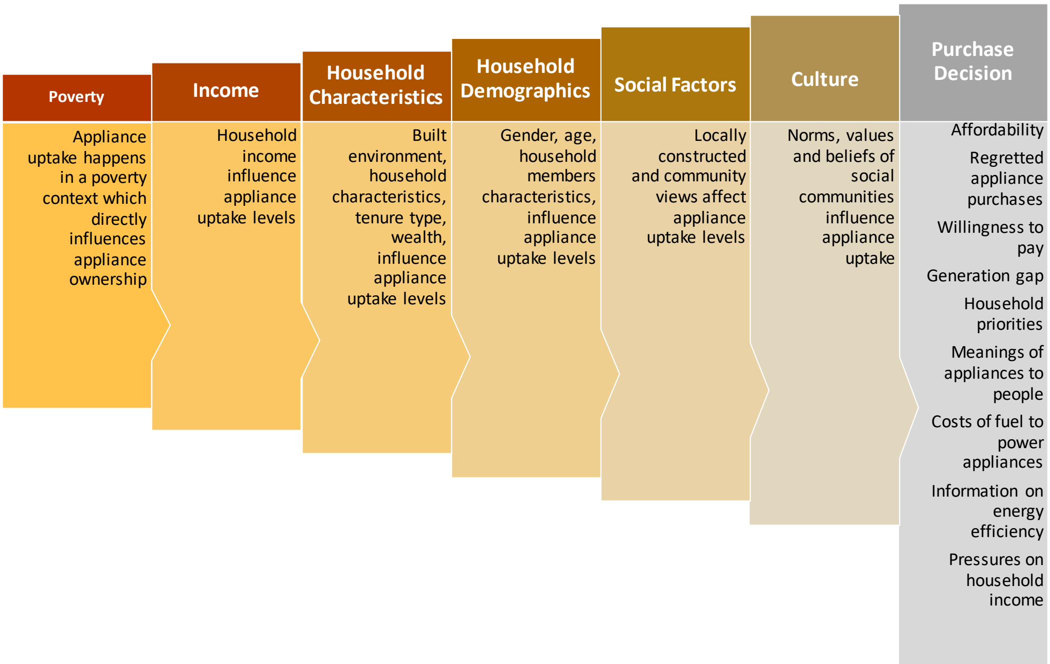


Fig 2. Authors synthesis of the factors influencing social shaping of appliance uptake in low-income communities based on current literature

2.3 Disruption innovation to foster socially inclusive energy transition in rural areas

Disruptive innovations do not attempt to bring better products; instead, they disrupt and redefine the existing market trajectory by introducing products and services that are more convenient, more straightforward and less expensive (Christensen, 2013). Disruptive innovation plays a vital role in energy transition theory as it emerges from constructivist sociology and evolutionary economics (Paredis, 2011; Schot & Geels, 2008; Winskel & Radcliffe, 2014). Transition theorist often presupposes that disruptiveness is a requirement for system innovation, however, among modern thinkers, transition theory has been more attendant to broader societal structures and institutions (Markard, Raven, & Truffer, 2012; Winskel, 2018a). In energy system-based transition, innovations have a distinctive emphasis on the hierarchy that creates barriers for sustainable innovations and transitions (Rosenkopf & Tushman, 1992). Azimoh et al., (2017) demonstrated such barriers in micro-grid transition in rural Africa and reported that technological transition and innovation must be complementary to the renewable transition to enable higher uptake of appliances. As mentioned in section 2.1, the lack of such complementary planning of technological innovation and appliance uptake often results in the long-term failure of off-grid rural electrification systems due to system lock-in (Julius et al., 2014).

Moreover, it is the uncertainty in the electricity load prediction among rural consumers that reduce the performance of off-grid systems. The complex causes of this uncertainty are illustrated in Table 1 and Fig 2, that cluster deeply around the social shaping dimensions of technology. Winskel, (2018) say that the disruption of the energy system is itself a necessary and welcome enabler of the shift to more sustainable and more rapidly decarbonised energy systems.

Building on Winskel, (2018)'s argument, we envisage that disruptive innovation in rural renewable energy transition (especially in sub-Saharan Africa) would mean replacing traditional energy sources and appliance with the modern form of electrical appliances. It would need replacement of traditional cooking stoves and charcoal irons through a socially inclusive electrical appliance uptake strategy which should be consumptive-productive-service sector-oriented (see Fig 1). To this effect, we use Christensen's theory of disruptive innovation (Christensen, 1997) and examines four questions; '*Are renewable energy providers in the market improving along a trajectory of sustaining innovation? Have renewable energy providers overshot customer needs? Do renewable energy providers possess the capability to respond to disruptive threats? Are energy providers floundering as a result of innovation?'* By answering these questions, we can identify three critical elements of disruptions, first, rate of improvement of appliance uptake. Second, we identify the distinctively different trajectory of improvements of the uptake of appliance in the study area. Third, is the critical element of understanding the pathways of sustaining and disruptive innovations. These elements of disruptive innovation are assumed to overcome current challenges associated with the socially inclusive transition in rural areas.

The challenges associated with socially inclusive energy transition in rural areas are those related to practicalities of implementation, location in remote areas with steep terrain and impoverished customers which affects sustainability, limited local technical and managerial skills, low energy demand, inadequate availability of supply components, and unproven financing models (Azimoh et al., 2017; EA, 2018). Public acceptance, social acceptance and local acceptance of renewable micro-grids are crucial for inclusive transition (Musall & Kuik, 2011a; Zoellner, Schweizer-Ries, & Wemheuer, 2008)[1]. Community co-ownership (COO) has been widely discussed in the literature as a disruptive strategy of local acceptance of renewable micro-grids (Musall & Kuik, 2011b; Ruggiero, Onkila, & Kuittinen, 2014; Walker, 2008). Based on this evidence, we examine the pathways for disruptive innovation for better appliance uptake in Rwanda and establish a pathway for consumptive-productive-service sector-oriented appliance uptake approach.

[1] These studies are based on German-context, but the policy implications are widely applied across the Global South context.

3. Data and method

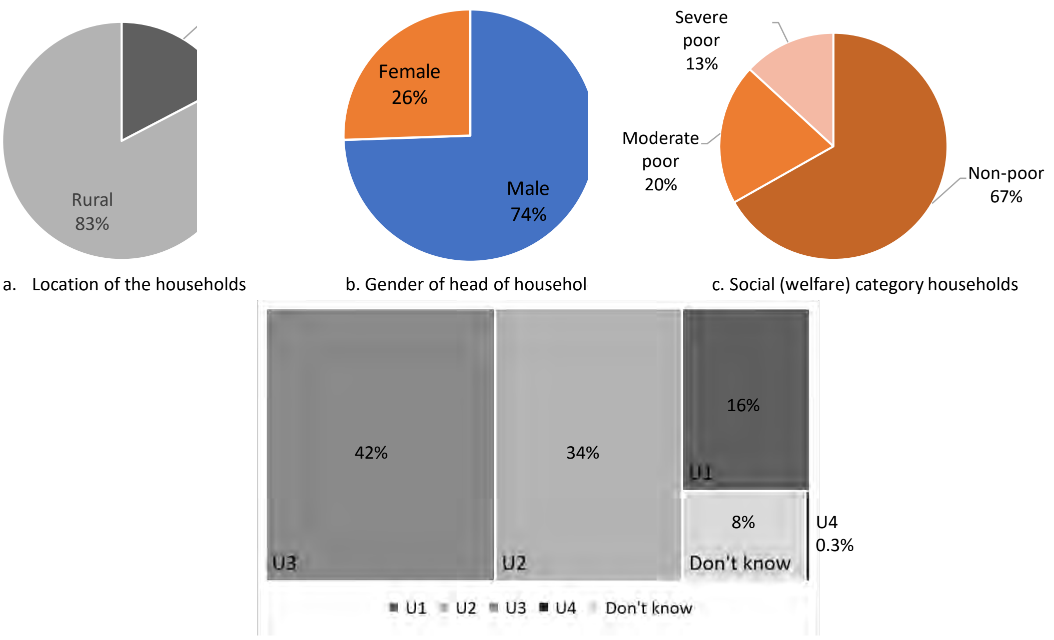
3.1 Data

This study is based on Rwanda Integrated Household Living Survey (EICV) dataset for the year 2010/11 (EICV3), 2013/14 (EICV4) and 2016/17 (EICV5). The EICV5 dataset interviewed 14,580 households, representing 64,314 people (NISR, 2018). The EICV5 survey shows that 38.2% of the population was poor in 2016/17, as compared to 39.1% as measured by the EICV4 survey of 2013/14. During the same period, extreme poverty went from 16.3% to 16.0% (NISR, 2018). The EICV5 report also states that the reduction in poverty between EICV5 and EICV4, respectively, was not statistically significant. The poverty gap rate, which measures the gap between people's spending and the poverty line, also showed a non-significant change to 11.7 in 2016/17, from 12.0 in 2013/14 (NISR, 2018). The summary of inequality and poverty rate for 2010-2017 is shown in Table 2. The population of Rwanda is 12.63 million (as per 2019) with more than 70% of the population living in rural areas (World Population Review, 2019). The demographic characteristics of the households analysed in this study as per the EICV5 dataset are illustrated in Fig 3.

Table 2. Summary of inequality and poverty rates in Rwanda (2010-2017)

	EICV3: 2010/11	EICV4: 2013/14	EICV5: 2016/17
Gini coefficient	0.49	0.44	0.42
Headcount poverty rate	44.9*	39.1*	38.2
Poverty gap rate	14.8*	12.0*	11.7
Sample size	14,308*	14,419*	14,580

(Source: NISR, EICV3, EICV4, EICV5. Note: *includes panel sample)



a. Location of the households b. Gender of head of househol c. Social (welfare) category households

d Ubudehe category of the households

Fig 3. Demographic characteristic of the households under study (n = 14,580)

In 2007, the Government of Rwanda (GoR) launched its Economic Development and Poverty Reduction Strategy (EDPRS) of which Vision 2020, is part of its strategy to address the three pillars of sustainable growth for jobs and exports, Vision 2020 *Umurenge* Program (VUP) and good economic governance. The VUP is an Integrated Local Development Program to 'Accelerate Poverty Eradication, Rural Growth, and Social Protection'. It uses the existing decentralisation system and leverages technical and financial assistance to accelerate the rate of poverty reduction in Rwanda. The aim is to eradicate extreme poverty by 2020 (GoR, 2007). The VUP is organised around three components, first intends to revive public works through community-based approaches. Following components innovate with credit packages to tackle extreme poverty as to foster entrepreneurship and off-farm employment; and the third components includes direct support to improve access to social services and basic amenities (GoR, 2007). This study aims to contribute to the VUP strategies by forwarding socially inclusive energy transition pathways. Additionally, the gendered perspective employed in this study aligns with VUP's strategy of economic growth enabler by off-grid electrification of small and medium enterprises in rural areas (GoR, 2007).

The GoR envisions 100% electricity access by 2024, with 52% on-gird and 48% off-grid electricity generation. It currently has 218 megawatts (MW) of installed generation capacity, and its national electrification rate is estimated to at 30% (12% in rural areas, 72% in urban areas) (USAID, 2018). The present installed capacity is illustrated in Fig 4; there are 1.7 million households without power in 2018. The current challenges in electrification include misalignment of power supply and demand, limited financing for off-grid companies and limited affordability of electricity solutions for rural households and businesses (USAID, 2018). Through this study, we intend to create higher off-grid appliance uptake pathways for socially inclusive energy transition (as mentioned in section 1).

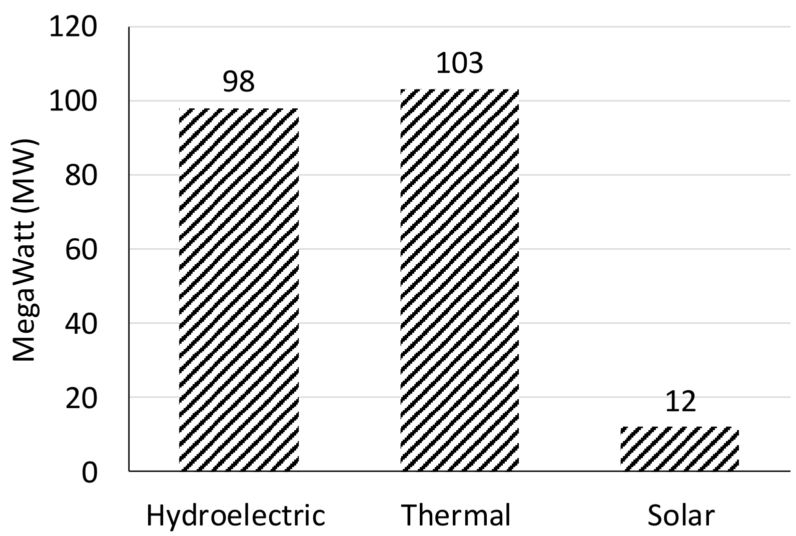


Fig 4. Installed capacity in Rwanda, 2018 (Source: (USAID, 2018)).

3.2 Analysis

A binary logistic regression model is used to examine the drivers of appliance ownership and investigate the influence of location of household, the gender of the head of household (HoH), population consumption quintiles, social (welfare categories) and the *Ubudehe* category. In Rwanda, social class is ranked using the Ubudehe welfare ranking. Ubedehe is a traditional community-driven collective action of solving problems. It is Rwanda's best known indigenous solution to poverty alleviation (RGB, 2019). The Ubudehe categorisation is crucial to the success of the VUP program for efficient resource allocation and direct credit transfer mechanisms. The Ubudehe categorisation is illustrated in Table 3, where, it is logical to imply that lower categories (1 & 2) would own a smaller number of household appliances than the higher categories (3 & 4). Besides, based on the GoR's definition and categorisation of the Ubudehe categories, we assume that category 1 are in *extreme poverty* who cannot afford even the basic electrical appliances, and exclude it from the regression model. Similarly, social (welfare) category classifies the population-based on poverty line RWF 159,375 (~USD 168) per year. Population living above it are categorised as 'Non-poor', where population below RWF 105,064 (~USD 110) per year are identified as 'Extremely/Severely poor' (see Table 4).

Table 3. Ubudehe categories as per the Government of Rwanda (source: (Ezeanya-Esiobu, 2017))

Ubudehe category	Characterisation
Category 1	Very poor and vulnerable citizens who are homeless and unable to feed themselves without assistance.
Category 2	Citizens who can afford some form of rented or low class owned accommodation, but who are not gainfully employed and can only afford to eat once or twice a day.
Category 3	Citizens who are gainfully employed or are even employers of labour. Within this category are small farmers who have moved beyond subsistence farming, or owners of small and medium scale enterprises.
Category 4	Citizens classified under this category are chief executive officers of big businesses, employees who have full-time employment with organizations, industries or companies, government employees, owners of lockdown shops or markets and owners of commercial transport or trucks

The primary dependent variable of appliance ownership in the EICV5 dataset is examined through the question *'How many durables does your household own?'* It enlists 29 electrical and non-electrical durables, (of which 20 were electrical appliances), with electrical appliance ownership is treated as a binary variable (1 = Yes, 0 = No). The variable list is illustrated in Table 4. See appendix for descriptive statistics of the variables and its correlogram.

Table 4. Variable list and their description

Dependent variable	Data type (Binary: 1 = Yes, 0 = No)	
Appliance type	[1] Radio with or without CD player; [2] Mobile telephone; [3] TV set; [4] Satellite dish; [5] Video/DVD player;	[11] Electric fan; [12] Sewing machine; [13] Refrigerator/freezer; [14] Electric generator; [15] Electric hotplate;

	[6] Decoder; [7] Music system; [8] Computer and accessories; [9] Cooker; [10] Laundry machine;	[16] Power stabiliser; [17] Still camera; [18] Video camera; [19] Printer; [20] Water filter
Independent variable	**Data type (Discrete)**	**Descriptive**
Location of household	Rural; Urban [REF]	[Note: Since the scope of this study is rural-centric. We use the urban variable as a reference [REF] category in the analysis]
Ubudehe category	Category 1 (U1); Category 2 (U2); Category 3 (U3); Category 4 (U4) [REF]	Category 4 (see Table 3) is used as a reference category.
Gender of the head of household (HoH)	Female Male [REF]	[Note: We report only the 'female' gender related results. Male is the reference category]
Quintiles	Q1: poor Q2 Q3: middle Q45: rich [REF]	Consumption quintiles as per EICV5 classification (NISR, 2018). The Q4 and Q5 (Q45) is the reference category, classified as rich households.
Social (Welfare) categories	[1] Severely poor [2] Moderately poor [3] Non poor [REF]	Poverty classification as per the NISR (2018) EICV5 dataset. The poverty line is drawn at RWF 159,375 (~USD 168) per year and the extreme poverty line at RWF 105,064 (~USD 110) per year. [1 USD = 947.25 RWF; Dec 2019 rate]

In this study, under the binary logistic model, the estimated value of the dependent variable (Appliance = 1; Non-appliance = 0) is interpreted as the probability that the technology diffusion of an appliance in a household (HH) is driven by the explanatory independent variables (as per Table 4). The empirical model is represented as (see eq. 1),

$$Y_i = b_0 + b_1 Location_i + b_2 Gender_i + b_3 Social_i + b_4 Quintiles_i + b_5 Ubudehe_i + u_i \quad (1)$$

$$\begin{cases} y_i = 1 \; if \; a \; particular \; appliance \; is \; present \\ y_i = 0 \; if \; the \; particular \; appliance \; is \; not \; present \end{cases}$$

where, Y_i is a binary variable indicating whether the specific appliance is owned by the HH (Yes/No); Jun, Kim, Jeong, & Chang, (2010) also performed a similar contingent valuation methodology employing dichotomous variables. A binary Dummy variable (1 = Yes, 0 = No) for each of the appliances (see Table 4) was created to fit the definition of Y_i. The aim is to determine how each appliance has penetrated within the social context of the independent variables, and the likelihood of its diffusion based on the location, gender, social category and Ubudehe category (as illustrated in eq. 1). Epistemological evidence from the literature show that non-income drivers (like the independent variables of eq. 1) promote higher likelihood of technology diffusion (appliance uptake) in poverty that is critical in designing social inclusive energy transition policies (see Table 1 and Fig 1). $Location_i$ is also a binary dummy variable (1 = Yes, 0= No) accounting for 'rural' location. $Gender_i$ is a dichotomous variable that explains the gender of the head of household (HoH), with Male = 1 and Female = 0. Binary dummy variables for social categorisations ($Social_i$) accounted for each of the welfare categories (see Table 4) as 1 = Yes, 0 = No. Similarly, the five quintiles ($Quintiles_i$) are accounted for as binary variables (1 = Yes, 0 = No) by creating dummy variables for each of the quintiles (Q1, Q2…, Q5). Referring to the NISR (2018) EICV5 classification, we merged the high-income consumption quantile Q4 and Q5 as Q45 to improve the interpretability of the results. Besides, Q4 and Q5 had non-parametric characteristics that $Ubudehe_i$ represented four categories (2 …, 4, see Table 4), and dummy variables were assigned to create binary values for each of the categories (1 = Yes, 0 = No); u_i is the error term. The modified equation is illustrated in eq.2.

$$Y_i = b_0 + b_1 urban_{i[REF]} + b_2 rural_i + b_3 male_{i[REF]} + b_4 female_i + b_5 nonpoor_{i[REF]} + b_6 moderatepoor_{i[REF]} + b_7 severepoor_i + b_8 Q1_i + b_9 Q2_i + b_{10} Q3_i + b_{11} Q45_{i[REF]} + b_{12} U1_i + b_{13} U2_i + b_{14} U3_i + b_{15} U4_{i[REF]} + u_i \quad (2)$$

$$\begin{cases} y_i = 1 \; if \; a \; particular \; appliance \; is \; present \\ y_i = 0 \; if \; the \; particular \; appliance \; is \; not \; present \end{cases}$$

4. Results and discussion

The EICV5 micro dataset that surveyed 14,580 households recorded appliance ownership as household durables (as reported in section 3.2, Table 4), Fig 5 shows the distribution of gendered appliance ownership as in urban and rural Rwanda. It can be observed that information and communication technologies (ICT) devices like radio and mobile phones have the most appliance uptake across the rural (78.7%) and urban (36.7%) household with 93.9% of the mobile phones are owned by the male head of households (HoH), female-headed household showed 21.6% of the total mobile phones ownership. Welfare appliance like the refrigerator and washing machine uptake is low across the rural-urban boundaries of Rwanda. It can be seen from Fig 5 that rural households had 11.8% of laundry machine (washing machine) uptake where the urban area has a 1.6%. The refrigerator (including freezers) uptake is 0.10% urban and 0.08% rural, with more male representation in the appliance uptake. Appliances like TV sets and fans had higher uptake in the urban areas (6.6% and 6.5%, respectively) with a strong male-centralism (8.6% and 9.7%, respectively). Cooker shows higher appliance uptake in the rural area; however, it is a combination of both electrical and non-electrical variants. Also, hyper-modern and skill-generating appliance uptake like computers were high in urban areas (3.4%), and, male-centric (3.6%). Computer uptake by female is 0.7% of the surveyed sample. Fig 5 distinctively indicates the gendered appliance uptake pattern in Rwanda.

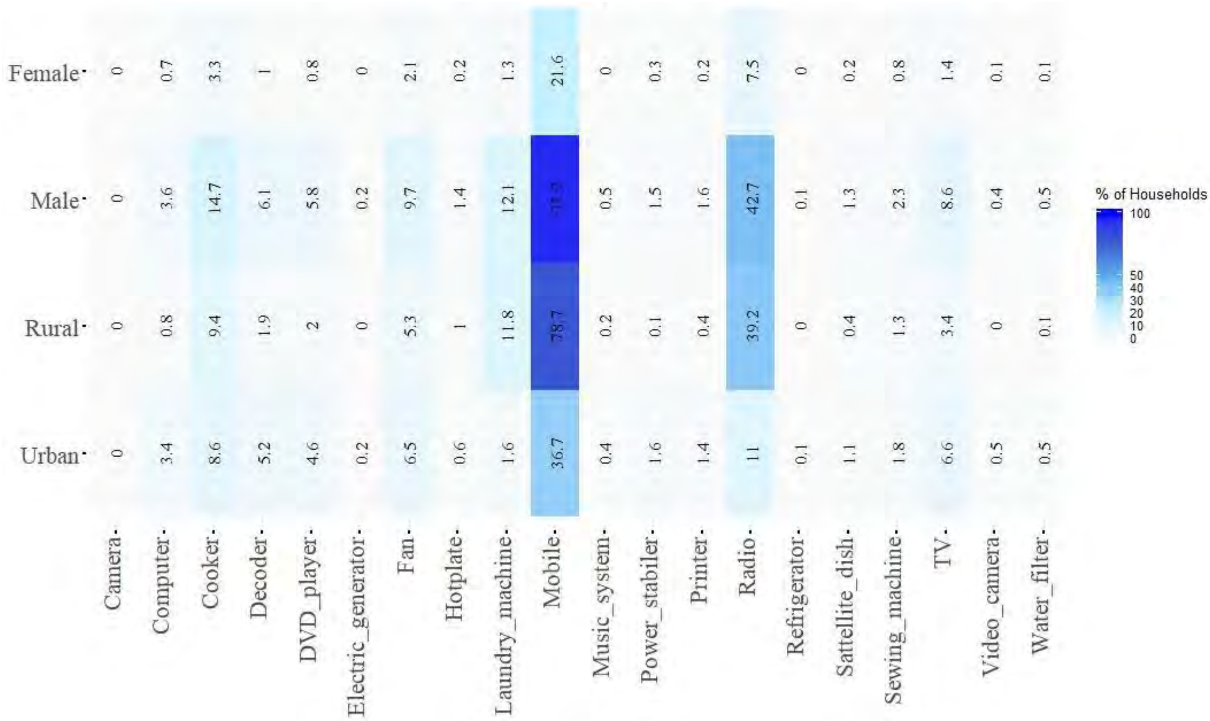


Fig 5. A heatmap illustrating gendered appliance ownership in urban and rural Rwanda (n = 14, 580)
[Note: Male and Female are referred to the gender of the head of household (HoH); of which 75% were males and 25% were female, according to ECIV5 survey demographic characteristics (NISR, 2018)]

Further breakdown of dominant ICT device uptake is illustrated in Fig 6 that shows that most of the households had at least one mobile phones. However, radio ownership is at a maximum of 1 radio per household, most of the households have no radios, even though it has a higher ownership frequency (see Fig 5). Mobile phone driven ICT diffusion across socio-economic layers have been reported to have distinctive social and sustainable development impacts, especially for women and low-income communities (Nurullah, 2009; Wajcman, 2007). From a social shaping of technology perspective (SST), mobile phones (ICT) diffusion have helped micro-entrepreneurs in rural Rwandan communities to expand their business by developing new business and social networks (Donner, 2006). The higher penetration of mobile phones, as illustrated by the EICV5 dataset (see Fig 6), shows better prospect for the realizability of the VUP (Vision 2020 *Umurenge* Program) program to foster Rwanda's sustainable development goals.

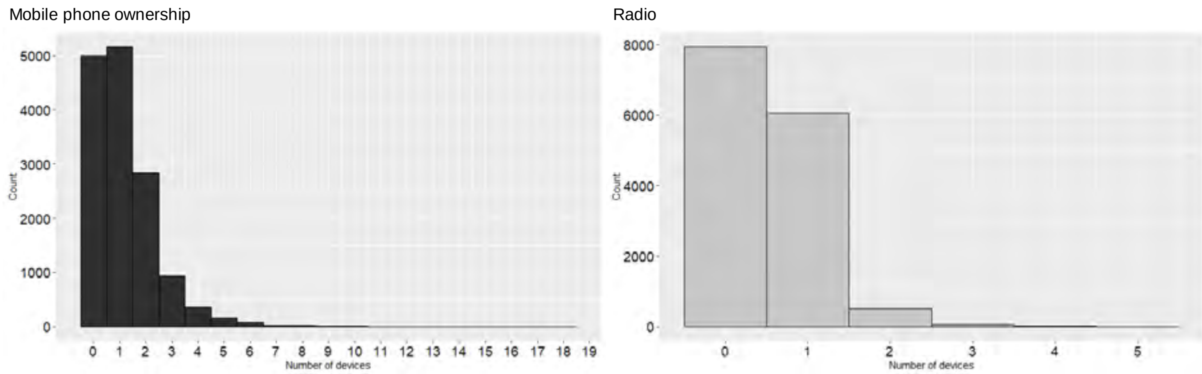


Fig 6. Household ICT device ownerships in Rwanda (n = 14,580). [Note: Y-axis shows number of household (count); X-axis shows the number of devices]

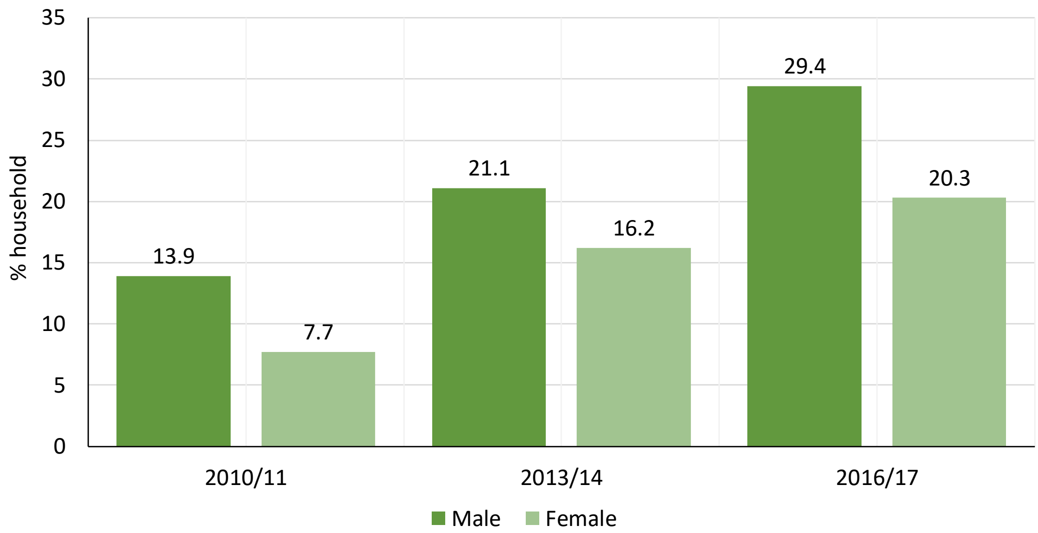


Fig 7. Household with electricity as the main source of lighting by the HoH gender (Source: EICV3 (n = 14,308), EICV4 (n = 14,419) and EICV5 (n = 14,580) dataset)

Apart from ICT devices, the electrification rate is also a key indicator of development, especially concerning the progress in UN SDG – 7. A descriptive panel data representation of EICV 3, EICV 4 and EICV 5 dataset show that overall share of electric lighting (bulbs, tube lights, LEDs, etc) has increased between 2010 to 2017 (see Fig 7). More importantly, the diffusion of solar-lighting devices illustrated the progress in off-grid electrification in Rwanda (see Fig 8). The overall uptake of solar-based lighting is increasing, with 0% share in 2010/11 to approximately 13% in 2016/17; of which 8.3% was owned by male HoH and 4.5% by female HoH (see Fig 8). Higher influx of off-grid solutions like solar home lighting systems shows the further propensity of appliance uptake (from the SST perspective) in Rwanda that can help the government to realise its poverty alleviation and the national VUP targets

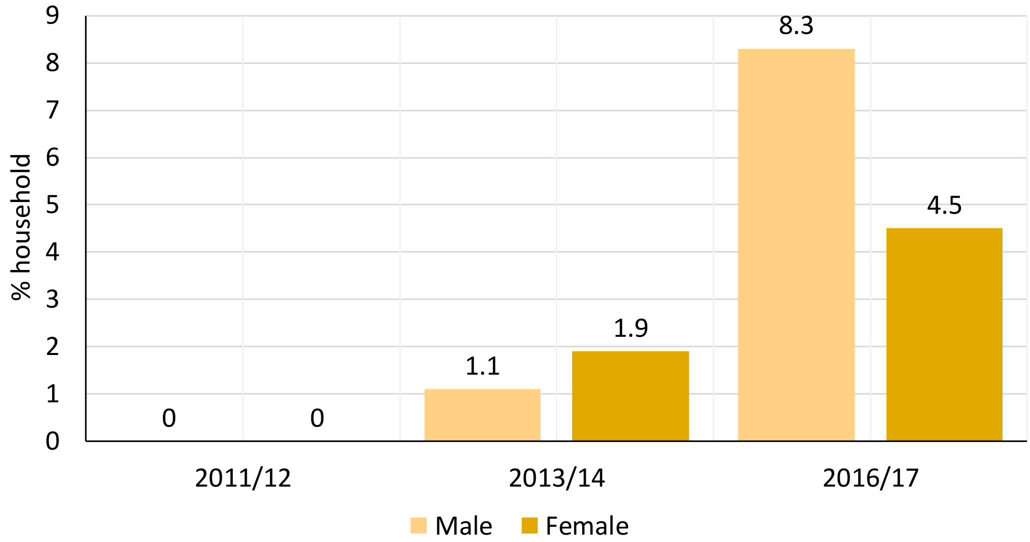


Fig 8. Household with solar panel as the main source of lighting by the HoH gender (Source: EICV3 (n = 14,308), EICV4 (n = 14,419) and EICV5 (n = 14,580) dataset)

The appliance uptake among the welfare categories of Rwanda (Ubudehe, see Table 3) shows a distinct distribution of appliances across it (see Fig 9). The appliance uptake in U1 and U2 show higher ownership of radio and mobile phones; however, categorically the diffusion of fans, laundry machines and TVs are higher in the U2 category. Further segmentation of the appliance ownership is distinct in the U3 and U4 of the Ubudehe categorisation (see Fig 9). It can be interpreted as the middle-class (and higher) way of consumption. The upper socio-economic consumption pattern is evident in the '*Don't know*' category, where there is characteristic mix of hyper-modern appliances that improve the 'convenience' factor of daily life, vis-à-vis higher household welfare. This argument is based on Sovacool's interpretation of energy service ladder across the socio-economic segment (see Table 5 of (Sovacool, 2011)).

As discussed in section 2, lower-income (and some middle-income) households in Global South portray a dynamic energy stacking behaviour that creates a mix of traditional and modern appliance uptake shapes the uptake of a specific technology. Interestingly, this study shows that mobile phones and radio (both ICT-devices) penetrated across the socio-economic sections of Rwanda (see Fig 6 and Fig 9) that creates a platform for ICT-driven sustainable development policies for meeting the targets of VUP. Donner, (2006) have reported that an increase in mobile phone ownership among the rural areas expanded microentrepreneurial network for grassroot-businesses. Future off-grid planning in Rwanda must account for this ICT-diffusion, especially to reduce the gendered disparity in its ownership (as illustrated in Fig 5), and to foster ICT-driven sustainable development. Better access to ICT-devices, especially for women, would empower them and help them build a more resilient rural-business network, which is crucial for disruptive innovation in resource-constrained and low-income communities (Nogami & Veloso, 2017).

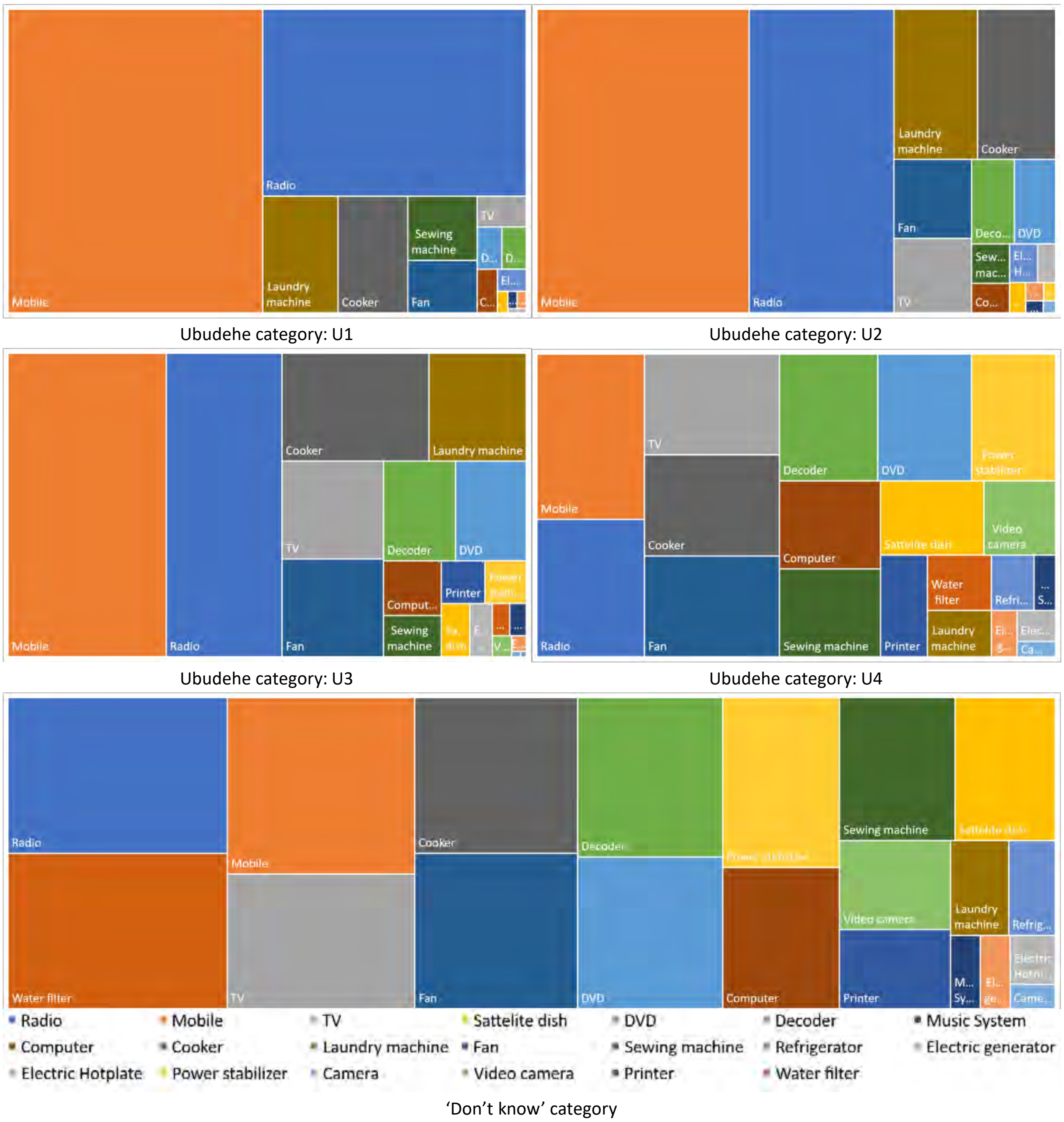


Fig 9. Appliance uptake as per the Ubudehe categories in EICV5 dataset (n = 14,580)
[note: 'Don't know' category is a mixed category where the respondents did not know their Ubudehe category, as per the EICV5 datasheet (NISR, 2018)]

The binary logit regression results are presented in Table 5 and Table 6, explain the interdependencies between appliance uptake and its drivers. The socio-economic and gendered drivers considered (see Table 4) in this study were drawn from epistemological evidence from the social shaping of technology (SST) and its effect on appliance uptake (see Table 1 and Fig 2). Appliance-wise uptake analysis shows that devices like mobile phones, radio, TV, cooker (electric and non-electric) and fan have a higher probability of uptake (see Fig 10). In general, the appliance uptake is highly gendered and location specific in Rwanda, which is a critical clue for SST. Based on the reference cases [REF], it can be seen from Table 5 and Table 6 that 'urban' location and 'male' dominate the appliance ownership across the spectrum of socio-economic variables under study (see eq 2). Moreover, the cluster of significant coeffecient of appliance ownership can be found in higher income Ubudehe (U3 and U4) and income categories (Q45), see Table 5 and Table 6.

Information and communication technology (ICT) devices have higher appliance ownership across the consumption quintiles, income groups and the Ubudehe categories (see Table 5). The positive sign of the regression coefficient between radio ownership and social(welfare) category shows that this device has higher probability of ownership among the non-poor (Odds Ratio (OR) = 1.807) and moderately poor (OR = 1.419) categories. The predicted probabilities across the households are illustrated in Fig 10. Besides, the likelihood of radio uptake by male is higher belonging to higher income Ubudehe categories (U3 and U4). However, it decreases across the U1 category (see Table 5). Similarly, mobile phone ownership has higher likelihood of uptake in the urban areas (OR = 10.319) and among the male members (OR= 1.867). Positive relationship is also amongst the higher income Ubudehe categories, while the negative signs across the social (welfare) categories shows mobile-phone ownership may be independent of the relative welfare status.

While ICT devices are critical modern indicators of SST (also mentioned in section 2), the demand of energy service for comfort, convenience and cleanliness (3Cs, after (Shove, 2003)) is also critical indicator of distributive justice, especially in low-income housing (R. Debnath et al., 2020). The convenience devices/appliances save time that have welfare effects (Sovacool, 2011). Convenience appliances uptake like TV, Refrigerator, Laundry machine, Computer, Electric hotplates and sewing machine shows a significant skewness towards male-dominance and social-economic hierarchical categories (see Table 5 and Table 6). TV has the highest likelihood of uptake in the Ubudehe categories U3 (OR = 3.044) and U4 (OR = 12.862), respectively (see Table 5). Whereas the U1 category, has a negative correlation with the TV uptake (see Table 5), indicating socio-economic barriers. A similar negative correlation paradigm can be observed between TV uptake and the social (welfare) categories, which indicate there may be other SST-forces influencing its uptake.

Laundry machine and refrigerators are critical welfare appliances in low-income households that reduces the drudgery of women by saving time (Dhanaraj et al., 2018). In Rwanda, the likelihood of uptake of laundry machine is higher among the higher income Ubudehe categories, U2 (OR = 1.851), U3 (OR = 2. 269) and U4 (OR = 2.852) with a significant male dominance (OR = 3.267) (see Table 5). The highest likelihood of refrigerator ownership is among the U4 category (OR = 12.930) showing high income-based inequality in welfare appliance uptake in Rwanda (see Table 6). Similarly, the likelihood of the uptake electric hotplate decreases significantly in the rural areas (OR=0.786) and lower income households. It is highly likely that electric hotplate will be present in a male-headed household belonging to U3 (and above) categories (see Table 6). The dominance of higher income U3 and U4 categories in the total appliance ownership is also evident from Fig 9.

Interestingly, the ownership of cookers (both electric and non-electric) have a significant influence of location and social categories (see Table 5). The EICV5 dataset do not specify the type of cooker, however, our analysis shows that the rural location has a significantly negative effect on its ownership (OR = 0.166). It can due to widespread use of firewood for cooking in rural and low-income households. The use of firewood for cooking contributes to high indoor air pollution in rural Rwanda that has significant health burden, especially on women and children (Rosa et al., 2014). Furthermore, a higher likelihood exists among the moderately poor (OR = 2.178) and non-poor (OR = 3.368) households (see Table 5). Similar likelihood trend applies for the U2, U3 and U4 categories, respectively indicating that the SST behind cooking appliance ownership is highly income dependent. It has crucial policy implications for clean cookstove initiatives.

The energy service for comfort was primarily availed through fans, with negligible representation of energy-intensive equipment like air conditions (ACs) in the EICV5 dataset. The ownership and uptake of fan also has a high skewness towards the higher-income households (see Table 6). However, ownership of fans has the higher predicted probability, indicating its greater diffusion rate among the Rwandan households (see Fig 10). A critical appliance in Rwanda is the high ownership of power stabilizers in higher income household that can imply on the poor power quality in the country. The U4 (highest income) households have the highest likelihood of ownership of power stabilisers (OR = 21.181) as they have the greatest share of household appliances (see Fig 9). Thus, low-income households may also refrain from buying appliances due to power quality issues, such that unstable voltage and frequent load-shedding may damage the appliances. The repair of damaged appliances further causes economic burden, that may lead to a poverty trap in many households. Similar, causality between repair of appliances and poverty was also observed in low-income households in Mumbai, India (Ramit Debnath et al., 2019). These are the major SST forces of appliance uptake in Rwanda which have a strong location, higher-income and gendered influence. These forces will further shape the appliance uptake trajectory, as illustrated in Fig 10.

The associated SST drivers can help in realising a socially inclusive energy transition that can be productive-consumptive-service sector-oriented at the local level, especially focussing on the predominant demographic: low-income rural households (see Fig 1). Section 1 and section 2 had drawn the evidence from the current literature and delivers four crucial pinch-points for disruptive innovation. These pinch-points are illustrated in Table 7 which are critical for socially inclusive energy transition in the rural and low-income areas as these areas need more appliance uptake for better household welfare.

Table 5. Estimated binary logistic regressions of appliance uptake in Rwanda. Results are presented as the β-coefficient value with its sign.

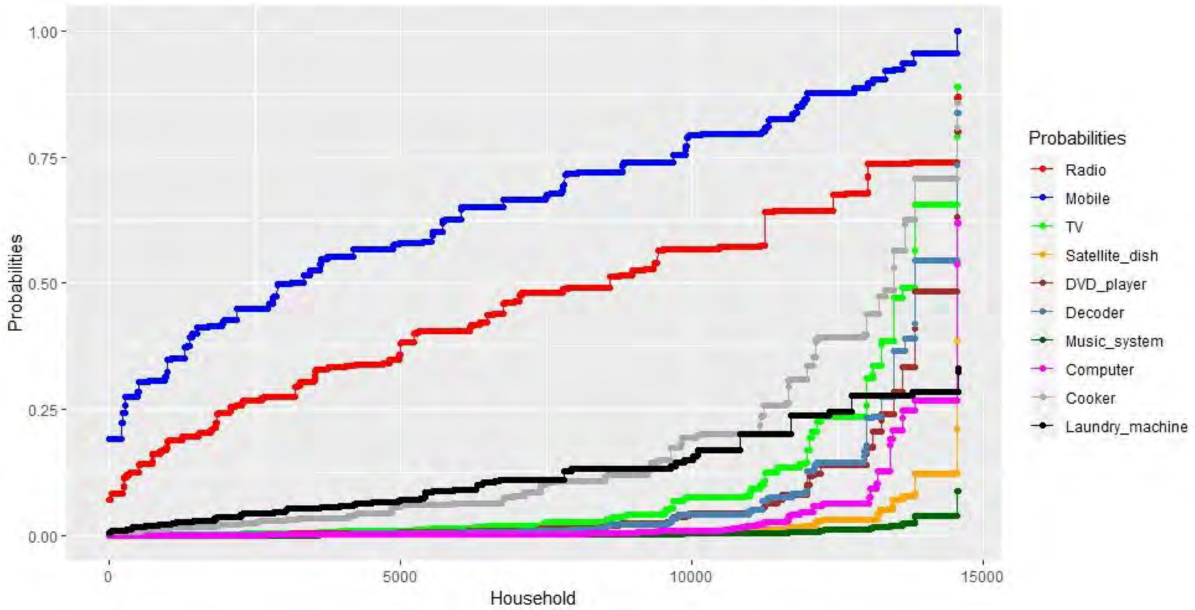
	Variables	Radio	Mobile phone	TV	Satellite dish	DVD player	Decoder	Music System	Computer	Cooker (Electric and non-electric)	Laundry Machine
Location	Rural									-1.798*	
										(0.166)	
	Urban [REF]		2.334**								
			(10.319)								
Social (welfare) category	Non_poor [REF]	0.592**								1.292**	
		(1.807)								(3.638)	
	Moderate poor	0.350**	0.303**							0.779*	
		(1.419)	(1.354)							(2.178)	
	Severe Poor										
Quintiles	Q1	-1.127***	-1.405***	-3.560***		-3.288**				-1.789***	-1.252***
		(0.324)	(0.245)	(0.028)		(0.037)				(0.167)	(0.286)
	Q2	-0.886***	-1.239***	-2.854***		-2.212***	-3.403**			-1.761***	-0.765***
		(0.412)	(0.290)	(0.058))		(0.110)	(0.033)			(0.172)	(0.465)
	Q3	-0.775***	-0.935***	-2.447***	-3.106***	-2.513***	-2.807***	-2.040***	-3.347***	-1.684***	-0.467***
		(0.461)	(0.392)	(0.087)	(0.045)	(0.081)	(0.060)	(0.130)	(0.035)	(0.186)	(0.627)
	Q45 [REF]	-0.455***	-0.607***	-1.317***	-1.475***	-1.279***	-1.364***	-0.930*	-2.140***	-0.938***	
		(0.635)	(0.545)	(0.268)	(0.229)	(0.278)	(0.256)	(0.394)	(0.118)	(0.392)	
Ubudehe category	U1	-0.184*		-1.117***		-0.852**	-0.933**		-1.066**		
		(1.202)		(0.327)		(0.427)	(0.393)		(0.344)		
	U2	0.627***	0.428***	0.438**		0.459**	0.422**		-0.829***	0.502***	0.616***
		(1.871)	(1.534)	(1.550)		(1.582)	(1.524)		(0.436)	(1.652)	(1.851)
	U3	0.933***	0.847***	1.113***	0.498*	1.085***	1.160***			1.125***	0.819***
		(2.541)	(2.323)	(3.044)	(1.646)	(2.961)	(13.795)			(3.079)	(2.269)
	U4 [REF]	1.779***		2.554***	2.621***	2.550***	2.624***		1.590***	2.041***	1.038*
		(5.927)		(12.862)	(13.748)	(12.813)	(1.881)		(4.904)	(7.699)	(2.825)
Gender	Female										
	Male [REF]	0.983***	0.624***	0.757***	0.626**	0.860***	0.632***	0.954*	0.330*	0.361***	1.184***
		(2.672)	(1.867)	(2.133)	(1.870)	(2.364)	(1.881)	(2.595)	(1.391)	(1.434)	(3.267)
Model-fit summary	Constant	-1.985	-1.063	-21.885	-21.762	-21.979	-21.139	-21.113	-21.498	-1.418	-3.031
	Nagelkerke R Square	0.174	0.220	0.448	0.292	0.396	0.447	0.180	0.384	0.346	0.122
	Hosmer and Lemeshow Test (Chi-square)		66.453***								16.465*

***, ** and * represent levels of significance at 1%, 5% and 10%, respectively. Odds-ratio are presented in parentheses. Reference cases are denoted as [REF]

Table 6. Estimated binary logistic regressions of appliance uptake in Rwanda. Results are presented as the β-coefficient value with its sign. (continued from Table 5)

Variables		Fan	Sewing Machine	Refrigerator	Electric generator	Electric Hotplate	Power stabilizer	Camera	Video camera	Printer	Water filter
Location	Rural					-0.578*** (0.786)					
	Urban [REF]										
Social (welfare) category	Non_poor [REF]										
	Moderate poor										
	Severe Poor										
Quintiles	Q1	-2.420*** (0.089)	-2.240* (0.106)			-2.443* (0.087)					
	Q2	-2.164*** (0.115)	-2.482* (0.084)								
	Q3	-1.793*** (0.166)	-1.414*** (0.243)			-0.800*** (0.449)				-2.697*** (0.067)	-2.501** (0.082)
	Q45 [REF]	-1.035*** (0.355)	-1.653*** (0.191)				-2.466*** (0.085)		-2.700* (0.067)	-1.659*** (0.190)	-1.814*** (0.163)
Ubudehe category	U1	-0.431* (0.662)									
	U2	0.367** (1.443)	-0.584** (0.558)						-1.885** (0.152)		
	U3	1.047*** (2.850)		-1.537* (0.215)		0.876* (2.400)				0.744** (2.104)	
	U4 [REF]	2.766*** (15.888)	2.094*** (8.089)	2.560*** (12.930)	2.528* (12.535)		3.053*** (21.181)		2.001*** (7.399)	1.714*** (5.551)	2.191*** (8.944)
Gender	Female										
	Male [REF]	0.395*** (1.484)				0.569* (1.767)				0.610** (1.841)	
Model-fit summary	Constant	-21.548	-21.085	-21.730	-21.905	-21.711	-21.394		-21.18	-21.749	-21.852
	Nagelkerke R Square	0.306	0.175	0.433	0.291	0.074	0.445		0.401	0.326	0.258
	Hosmer and Lemeshow Test (Chi-square)		13.411*						16.523*		

***, ** and * represent levels of significance at 1%, 5% and 10%, respectively. Odds-ratio are presented in parentheses. Reference cases are denoted as [REF]



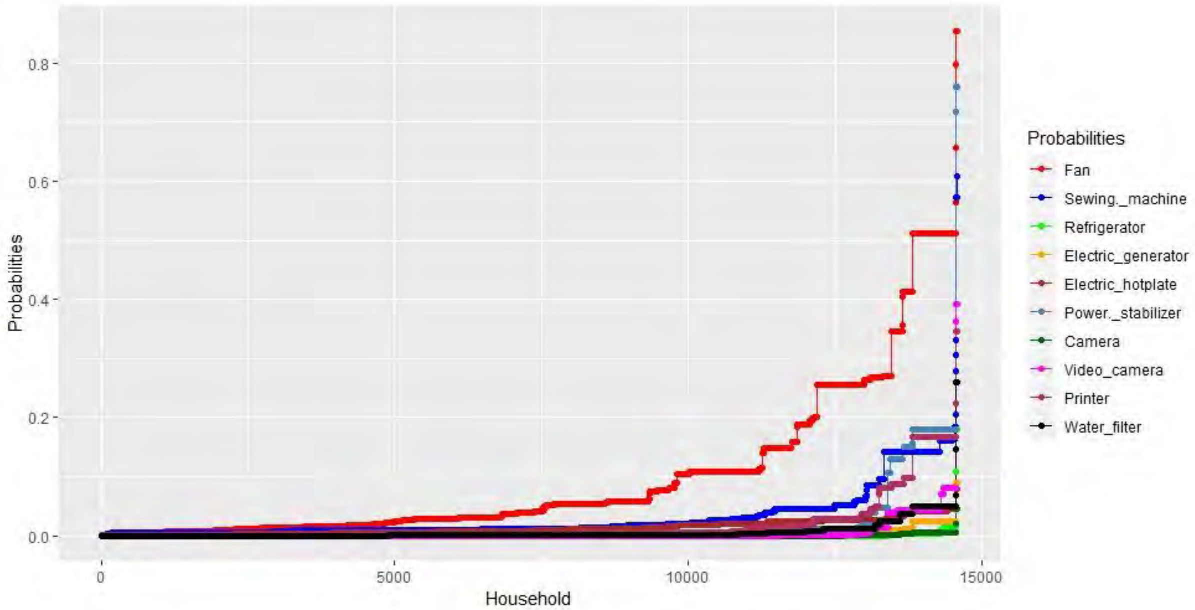


Fig 10. Predicted probabilities of appliance uptake in Rwanda (n = 14,580)

Table 7. Derived disruptive innovation pathways for Rwanda

Christensen's Theory of Disruptive Innovation action points (see Section 2.3)	Consumptive-productive-service sector appliance needs based on social shaping of technology in rural areas (extended from section 2.2 and 2.3)	Implications drawn from the regression analysis for socially inclusive energy transition in Rwanda
Sustaining innovation	• Improving the diffusion of appliances through frugal innovation in local markets, schools, healthcare centres, local para-transit transportation systems and household. The overall intention should target improving rural consumers' well-being.	• ICT-based devices like mobile phone, radio and TV has a higher likelihood of uptake in Rwanda. It remains a very gendered element, while mobile phones and radios are male-centric, the TV uptake likelihood was found to be higher among women-led households. • Innovating and developing a local ecosystem of mobile applications and energy services through

	• Creating local entrepreneurship driven financial models. • Skill development and community-led energy management initiatives.	ICT can promote inclusive energy transition and technology transfer. Success of such initiatives in Nigeria, South-Africa, Ghana and Kenya can be referred from Smith, (2014)
Overshooting consumer needs	Anticipating the uncertainties associated with household energy demand due to diffusion of electrical appliances will improve the resilience of off-grid renewable energy systems. It will in turn promote more appliance uptake across socio-economic classes.	• Likelihood of welfare appliance (laundry machine and refrigerator) is higher among the urban and U3 and U4 (middle to upper income) Ubudehe categories. Resources can be planned around this likelihood to support off-grid energy infrastructure in urban and rural localities with specific tariff plans. • Better and more equitable tariff plan as per the Ubudehe categories can promote energy justice during renewable energy transitions. Lessons can be learned from the ongoing VUP program.
Response to consumer threats	Conducting consumer-based surveys to determine consumer attitudes, behaviours, opinions, drivers and barriers of purchase. It can aid in creating better financial models, inclusive energy tariff plans and appliance market.	• This study showed ICT devices have the highest likelihood of uptake even in the poorest households in rural areas. Specific social policies around it can foster inclusive energy transition.
Floundering as a result of innovation	Increase system efficiency, reliability, provision of super-efficient appliances, reduce consumer tariffs and offer services that will improve consumer willingness to pay.	• Better welfare appliance provisioning in the U2 and U3 categories through innovation in e-governance and energy policing. • This study showed higher likelihood of power stabiliser ownership in high appliance households. It indicates towards power quality and reliability issues which must be addressed for improving energy affordability and accessibility across the socio-economic strata.

5. Conclusion and policy implication

This study investigated the social shaping of technology (SST) of appliance uptake in Rwanda using binary logistic regression on 14,580-household national survey micro dataset. The social shaping of technology perspective was used to derive disruptive innovation pathways for supporting socially inclusive energy transition in rural and low-income communities. An in-depth literature review also revealed critical epistemological themes in synergy with SST that drives appliance uptake across the household levels. In Rwanda, the social structure is as per the government’s Ubudehe scheme that categorises households based on their socio-economic capabilities. Statistical analysis results have shown that middle-income (U3) and middle-upper income (U4) households are more likely to uptake welfare appliances like refrigerator and washing machine (see Table 5 and Table 6, Fig 10). Understanding its uptake pattern is important because welfare appliances are implied to promote household welfare and well-being by empowering women. For a socially inclusive renewable energy transition, the diffusion of welfare appliance is essential even in the weaker socio-economic sections of the society. Off-grid rural electrification planning must account for welfare appliance provisioning in Rwanda and set up policy mechanisms to support higher uptake of such appliances. The Vision 2020 Umurenge Program (VUP) is one such local-development program that aims to accelerate poverty eradication, rural growth and social protection. Adding additional policy support for enabling higher uptake of welfare appliances in rural and female-led households can enhance the policy outcomes of the VUP program.

The diffusion of information and communication (ICT) devices like mobile phone and radio are the most widespread with highest probability of uptake in the Rwandan households (see Fig 10). It is a critical indicator that can shape ICT-driven energy governance and social development policies. A deeper penetration of mobile phones can provide a better and more robust ecosystem for mobile-based solar home system solutions. Success stories of such initiatives can be seen from Ghana, South Africa, Nigeria and Kenya; critical lessons can be learnt from Smith, (2014). Moreover, ICT-provides a robust micro-entrepreneurial platform for local business to grow and expand, successful business models are illustrated by Donner, (2006). The rise and success of M-Pesa in Kenya (Mas & Ng'weno, 2010) as a mobile phone-based financial bank also shows the importance of efficient utilisation of ICT-platforms. The ICT-driven M-Pesa's pay-as-you-go model is being utilised by disruptive solar companies (like M-Kopa Solar) to provide rent-to-own energy products. M-Kopa Solar is bringing in a low-cost, off-grid and socially inclusive energy revolution in Kenya (Shapshak, 2016). Such disruptive innovation is needed in Rwanda to create socially inclusive renewable energy transition.

From an off-grid power provisioning perspective, energy transition to renewables must address the SST drivers of appliance uptake to improve the reliability and inclusivity of energy planning. Besides, since a large portion of Rwandan households practice energy stacking and has a mix of both traditional and modern appliance, socially inclusive energy transition must account for such energy stacking behaviour. Incorporating energy stacking behaviour in off-grid renewable planning can aid in improving system stability and reduce uncertainty. It demands disruptive innovation in household appliances using renewables so that energy stacking and energy transition can remain coherent with the everyday household practices of Rwanda. Lessons can be learnt from India's off-grid private sector companies addressing energy poverty, as illustrated by Heynen, Lant, Sridharan, Smart, & Greig, (2019). Similarly, the likelihood of fan uptake is also high, which is an indicator of changing weather and climate. With Global South getting hot, more household will buy cooling devices, transitioning from fans to air conditioners (ACs) (Bardhan, Debnath, Gama, & Vijay, 2020). Understanding appliance uptake pattern and the social drivers shaping it can aid in better estimation of cooling demand in warming Global South, including Rwanda. It remains one of the critical global challenges associated with off-grid planning.

The findings of this study can aid in 'good' energy policymaking at a rural and low-income community level and aid Rwanda to push forward the VUP targets. With more efforts in renewable energy provisioning at the household and community level, a socially inclusive energy transition can promote distributive energy justice through higher appliance uptake, especially welfare appliances and ICT. Better tariff plans across the Ubudehe categories with sensible financial mechanisms will promote better appliance uptake. It can also encourage off-grid energy companies to design and implement more inclusive energy solutions in rural Rwanda. The way forward of this study would be to empirically investigate energy culture of rural Rwanda and link it with social shaping of technology theories that can aid in deriving granular details on the energy use practices, norms and usage pattern of the appliances. These details can help in reducing the uncertainties of rural energy systems and promote better investment in renewable off-grid and microgrid solutions.

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Appendix:

Summary statistics

	N	Mean	Std. Deviation	Variance	Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
Urban	14580	.17	.378	.143	.987	.041
Rural	14580	.83	.379	.144	.969	.041
Non_poor	14580	.67	.471	.222	-1.492	.041
Moderate_poor	14580	.20	.401	.161	.228	.041
Severe_Poor	14580	.13	.337	.114	2.805	.041
Q1	14580	.17	.373	.139	1.208	.041
Q2	14580	.18	.386	.149	.713	.041
Q3	14580	.20	.397	.158	.331	.041
Q4	14580	.21	.408	.167	.006	.041
Q5	14580	.24	.429	.184	-.566	.041
U1	14580	.16	.364	.133	1.543	.041
U2	14580	.34	.475	.225	-1.562	.041
U3	14580	.42	.494	.244	-1.901	.041
U4	14580	.00	.045	.002	481.167	.041
Male	14580	.74	.436	.190	-.742	.041
Female	14580	.26	.436	.190	-.742	.041
Radio	14580	.46	.498	.248	-1.969	.041
Mobile	14580	.66	.475	.225	-1.558	.041
TV	14580	.10	.297	.088	5.363	.041
Sattellite TV	14580	.01	.120	.014	63.811	.041
DVD Player	14580	.06	.243	.059	10.988	.041
Decoder	14580	.07	.253	.064	9.657	.041
Music	14580	.01	.071	.005	192.098	.041
Computer	14580	.03	.176	.031	26.130	.041
Cooker	14580	.17	.373	.139	1.187	.041
Laundry Machine	14580	.13	.333	.111	3.028	.041
Fan	14580	.10	.299	.089	5.195	.041
Sewing Machine	14580	.03	.171	.029	28.405	.041
Refrigerator	14580	.00	.027	.001	1320.909	.041
Electric generator	14580	.00	.045	.002	481.167	.041
Hotplate	14580	.01	.113	.013	72.181	.041
Power stabilizer	14580	.02	.128	.016	55.036	.041
Camera	14580	.00	.022	.000	2078.571	.041
Video camera	14580	.01	.071	.005	192.098	.041
Printer	14580	.02	.130	.017	52.893	.041
Water Filter	14580	.01	.075	.006	170.727	.041

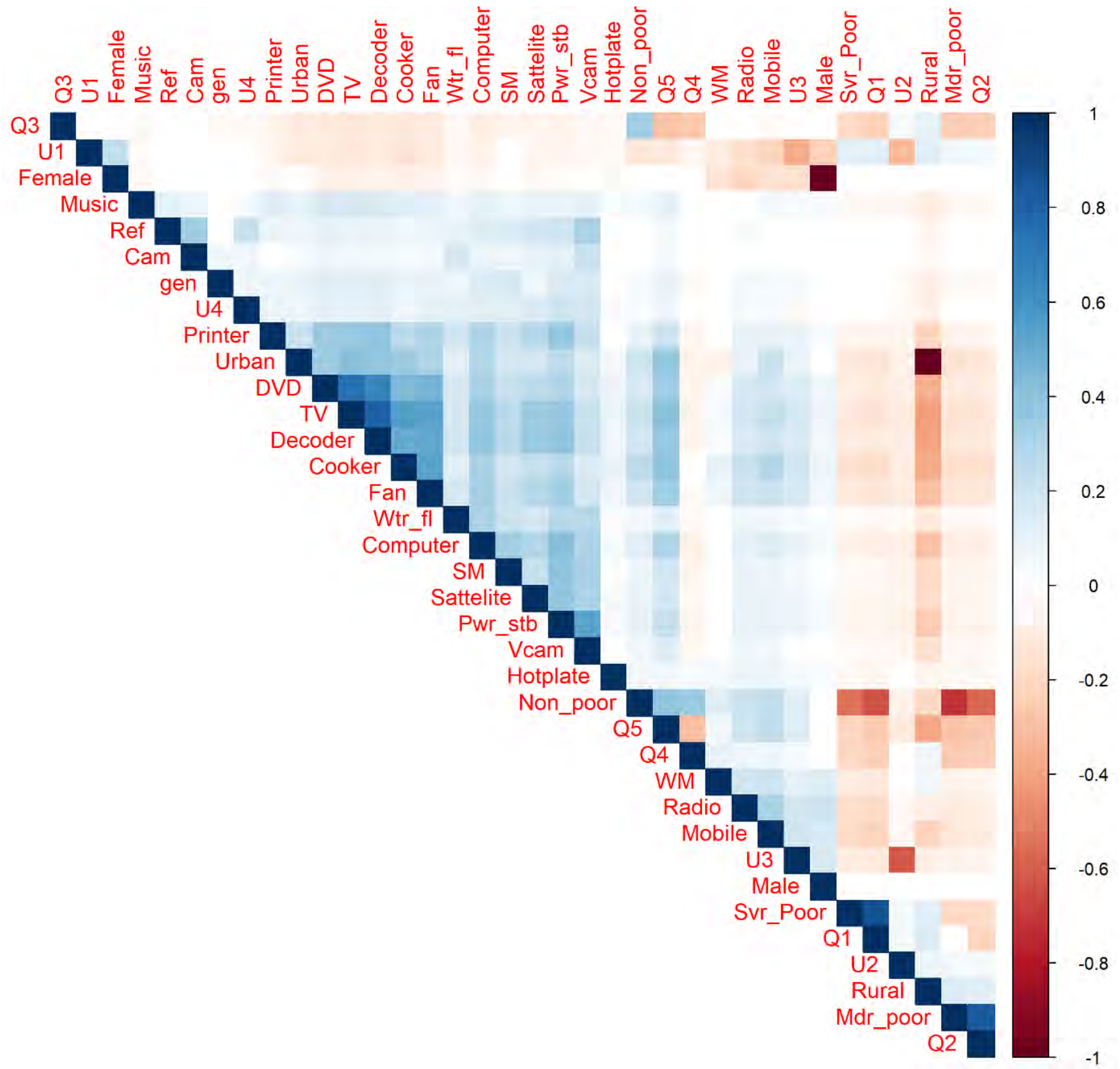

Figure 1. Correlogram of the variables (n =14580).

{Note: Correlations with p-value > 0.01 are considered as insignificant. These values are left blank. Positive correlations are displayed in blue and negative correlations in red colour. Colour intensity is proportional to the correlation coefficients. In the right side of the correlogram, the legend colour shows the correlation coefficients and the corresponding colours}