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Working Paper

Behavioural constraints in energy technology uptake: Evidence from real-purchase offers in rural Rwanda and Senegal

Ruhr Economic Papers, No. 1081

Provided in Cooperation with:

RWI – Leibniz-Institut für Wirtschaftsforschung, Essen

Suggested Citation: Bensch, Gunther; Grimm, Michael (2024) : Behavioural constraints in energy technology uptake: Evidence from real-purchase offers in rural Rwanda and Senegal, Ruhr Economic Papers, No. 1081, ISBN 978-3-96973-255-7, RWI - Leibniz-Institut für Wirtschaftsforschung, Essen,
<https://doi.org/10.4419/96973255>

This Version is available at:

<https://hdl.handle.net/10419/298848>

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RUHR

ECONOMIC PAPERS

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Imprint

Ruhr Economic Papers

Published by

RWI – Leibniz-Institut für Wirtschaftsforschung

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Ruhr Economic Papers #1081

Responsible Editor: Manuel Frondel

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ISSN 1864-4872 (online) – ISBN 978-3-96973-255-7

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Bibliografische Informationen der Deutschen Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie;
detailed bibliographic data are available on the Internet at <http://dnb.dnb.de>

RWI is funded by the Federal Government and the federal state of North Rhine-Westphalia.

<http://dx.doi.org/10.4419/96973255>

ISSN 1864-4872 (online)

ISBN 978-3-96973-255-7

Gunther Bensch and Michael Grimm*

Behavioural Constraints in Energy Technology Uptake: Evidence from Real-Purchase Offers in Rural Rwanda and Senegal

Abstract

Energy-efficient biomass cookstoves and small solar systems play a vital role in the transition to clean energy. Despite their affordability and scalability, their uptake remains low among households in sub-Saharan Africa. This paper examines the potential contribution of individual-specific behavioural factors to the under-adoption of these technologies. Drawing on data from real-purchase offers in rural Rwanda and Senegal, the analysis focuses on how the willingness to pay for the technologies varies with behavioural constraints including risk aversion, innovation resistance, time preferences, and beliefs. Our results confirm that these factors carry relevant variation that helps understanding the purchase decision process. These findings contribute to a better comprehension of consumer adoption behaviour of innovative consumer goods at the base of the pyramid, providing valuable insights for suppliers entering these markets and informing policy interventions aimed at facilitating households' transition to clean energy.

JEL-Codes: D12, O12, O13, O33, Q41

Keywords: Base of the pyramid; energy transition; willingness to pay; household decision; behaviour

May 2024

* Gunther Bensch, RWI; Michael Grimm, University of Passau and IZA. – Data collection underlying this research was financially supported by the Center for Development Research in Bonn (ZEF) and the Federal Ministry for Economic Cooperation and Development (BMZ). We thank Jörg Ankel-Peters, Nadine Kneppel, Luciance Lenz, and Maximiliane Sievert for their valuable support. We also thank the IB&C and CRDES teams for managing fieldwork, and all survey participants in Rwanda and Senegal. – All correspondence to: Gunther Bensch, RWI, Hohenzollernstrasse 1-3, 45128 Essen, Germany, e-mail: bensch@rwi-essen.de

1. Introduction

The slow progress towards universal access to affordable electricity and clean cooking technologies in sub-Saharan Africa remains the result of insufficient investment in infrastructure (IEA 2023), but also of limited uptake by households where the infrastructure is available (see Schmidt and Moradi 2023 for a recent example from Burkina Faso). Scaled-down transitional energy technologies are available to serve these populations outside the reach of electricity grids and cooking gas supply chains, but they also face adoption challenges. Energy-efficient biomass cookstoves (EEBCs) and small solar systems are such low-cost devices that provide essential lighting and cooking energy services more efficiently than traditional technologies, but are not necessarily emissions-free like clean fuels. Despite high private and plausibly positive social returns documented in the laboratory and in randomized field experiments under everyday conditions, the uptake of such consumer durables is still surprisingly low, i.e. households still operate with inefficient, costly and unhealthy devices (Mobarak et al. 2012; Grimm et al. 2020). Studies on products with similarly high returns such as malaria bed nets, water disinfectants and deworming medicines have found this ‘under-adoption’ as well (see, for example, Cohen and Dupas 2010 and Luby et al. 2008).

In this paper, we focus on individual-specific behavioural factors as potential reasons for the under-adoption of our two transitional energy technologies. Households’ willingness-to-pay (WTP) revealed in real-purchase offers serves to compare potential driving factors that we derive from the psychological, economic and marketing literature. We use WTP data collected with a method that incentivizes the disclosure of truthful preferences, the Becker-DeGroot-Marschak (BDM) method, combined with detailed information about consumer behaviour from Senegal for EEBCs and from Rwanda for solar devices.

We first review the evidence to show that private returns to households are indeed positive for both devices. Using standard econometric analyses, we also show that liquidity constraints matter, but can hardly explain the dominant part of the observed variance in uptake. We then motivate the role of various behavioural constraints including risk aversion, innovation resistance, time preferences, and beliefs and analyse their importance empirically using the same econometric framework to assess whether these factors correlate with households’ willingness to pay for the new technologies.

More generally, our findings contribute to a growing literature that seeks a better understanding of consumer demand of socially desirable household technologies designed for price-sensitive, resource constrained ‘base’ or ‘bottom of the pyramid’ (BoP) consumers (Prahalad 2012). BoP markets present significant departures from the assumptions of theories developed in an industrialized country context and decision-making behaviour of the poor differs significantly relative to the middle or upper class (Burgess and Steenkamp 2006; Narasimhan et al. 2015), market information is often not readily available in rural areas of low-income countries, and if so, it is less trusted (Lascu 2014).

More specifically, our findings add to the literature on household-level determinants of fuel and stove transitions (Lewis and Pattanayak 2012; Bonan et al. 2017; Kar et al. 2024).¹ Methodologically, our contribution is to add evidence based on willingness to pay to a literature that relied on stated preference methods and focused on technical parameters (e.g. Abdullah and Jeanty 2011; Johnson and Takama 2012; Sievert and Steinbuks 2020), partly also assessing risk and time preference (Jeuland et al. 2015; Carrasco-Garcés et al. 2021; Talevi et al. 2022). Previous research has emphasized the role of liquidity and credit constraints as well as imperfect information, yet they can typically only explain some of the variance observed in take-up (Beltramo et al. 2015; Grimm et al. 2020; Gaurav et al. 2011; Tarozzi et al. 2014). Lee et al. (2020) underpin the dominant role of costs by finding a sharp decrease in electricity connection rates in Kenya as fees increase: While almost all households connected if connection was for free, a subsidy equivalent to 57% or 29% increased connection rates by only 23 and 6 percentage points, respectively. Mekonnen et al. (2023) find a similar pattern for solar lanterns subsidies.

In their survey of the literature on the diffusion of agricultural technologies, Foster and Rosenzweig (2010) conclude that “ultimately the interplay between behaviour, market settings, traditional institutions and technology payoffs need to be addressed to more fully understand the variety of experiences over time and across countries in utilizing productive resources and adopting new technologies” (Foster and Rosenzweig, 2010: 25). In light of this interplay, this study does not aim to completely separate the influence of income and market

¹ As conceptualized by van der Kroon et al. (2013), energy transitions are driven by the household-internal opportunity set and the external political-institutional-market environment. Studies that also address these supply-side factors for transitional energy technologies in the sub-Saharan African context include Karanja and Gasparatos (2019) and Bensch et al. (2018, 2021).

imperfections, such as credit constraints, from our behavioural factors. Both types of factors have origins in rational decision-making and utility maximization. Instead of pinpointing which factors are the ultimate root causes, our objective is to enhance our understanding of how behavioural factors relate to technology adoption. This exploration seeks to determine whether the behavioural factors offer additional avenues for enterprises and policy to facilitate households' transition to clean energy.

The remainder of this paper is organized as follows. In Section 2 we provide the theoretical framework of our study, followed by the empirical setup in Section 3, where we also show the operationalization of the behavioral factors from our theoretical framework. Main results are presented in Section 4. We end the paper with a brief conclusion in Section 5.

2. Theoretical framework

This section lays out the theoretical framework on behavioural factors that may influence purchase decisions with respect to energy use, in order to derive hypotheses about the willingness to pay for EEBCs and solar lighting devices. We rely on consumer behaviour economic theory in general and innovation decision theory more specifically, accounting for the context of resource-poor consumers in developing countries. In line with the literature, we consider three types of household-specific behavioural factors: (i) risk aversion and consumer resistance, (ii) time preference, and (iii) experience and beliefs. We therefore do not address group-specific factors that may as well affect purchase patterns, such as local cultural features (Petersen et al. 2015) and social interaction (Miller and Mobarak 2014; Bonan et al. 2021; Alem and Dugoua 2022).

Risk aversion and innovation resistance

Innovations carry risks for consumers. The psychology and marketing literature captures risk aversion through consumer resistance, driven by perceived risk and habit (Ram 1989; (Ram and Sheth 1989). Perceived risk, in turn, includes the factors physical risk, economic risk, and functional risk. These risk perceptions are all well imaginable for our energy-access technologies. Not least, poor people may be reluctant to take the economic risk of larger initial investments, especially if there is a functional risk of new technologies in the form of faulty and counterfeit devices, as is the case in some small-scale solar markets (Mills et al. 2015). The second dimension of consumer resistance, habit, makes it difficult, and psycholo-

gically costly, for consumers to break with traditions and existing values and thereby to adopt new technologies (Rogers 2003). Traditional cooking practices are deeply embedded within cultural and social norms and households could, for instance, prefer food prepared over an open fire (Herington et al. 2017); people may also overestimate the necessary behavioural adjustment required to use a new stove (Dupas 2014). This innovation resistance could again impede the adoption of modern technologies. What is perceived as innovation resistance may, however, also reflect ability to pay or consumer choices for alternative frugal innovations, such as battery-driven lamps in the case of off-grid lighting solutions (Bensch et al. 2017). Similarly, how risk aversion affects the purchase decision eventually depend on the relative riskiness of old and new technologies as perceived by an individual, since sticking with an old technology obviously involves risks as well (Marra et al. 2003).

For the products considered in our analysis, Jeuland et al. (2015) find in their study relying on contingent valuation that risk-taking households place a lower WTP on fuel-efficient stoves.

Guided by these theoretical considerations, we test the following hypotheses:

H₁: The WTP decreases with risk aversion.

H₂: The WTP decreases with innovation resistance.

Time Preference

Poor consumers face more serious liquidity and credit constraints so that consumption cannot be smoothed over time via financing mechanisms and scarce resources have to respond to immediate necessities. This implies relatively higher time discount rates, where a higher weight is assigned to the present and a lower weight to the future, hampering the adoption of a new product that shares features of an investment good. In this context, households may also exhibit hyperbolic discounting or present bias in that they put more weight on consumption in t vs. $t+1$ than on $t+1$ vs. $t+2$, which is incompatible with standard assumptions of intertemporal utility maximization (see, for example, Duflo et al. 2011; Mahajan et al. 2020).

In the context of clean energy, Talevi et al. (2022) as well used contingent valuation and indeed found in their study on biogas cooking in rural India a lower WTP for fuel efficiency among household with a higher preference for the present.

Hence, we test the following hypothesis:

H₃: The WTP decreases with time preference, that is a preference for the present.

Experience and beliefs

Consumers form beliefs about the usefulness of a new technology. In the absence of own experience in using a new technology, households may rely on other sources of information about its benefits and inconveniences and how to use it appropriately (see e.g. Foster and Rosenzweig 2010). The literature describes this problem with three attributes of an innovation: ‘complexity’, i.e. the degree to which an innovation is perceived as being difficult to use, ‘observability’, i.e. the degree to which the results of an innovation are observable to potential customers, and ‘trialability’, i.e. the degree to which an innovation may be experimented with before adoption (Rogers 2003; Arts et al. 2011).

For the products considered in our analysis, Yoon et al. (2016) tested whether trial periods increase the WTP for solar lanterns in rural India but did not find any significant effect, different from Levine et al. (2018) who observed WTP-increasing learning effects from a free trial for EEBCs. The findings from Bensch and Peters (2020) and Meriggi et al. (2021) – like Yoon et al. (2016) and Levine et al. (2018) a real-purchase offer – also suggest that a (full life cycle) trial has a positive effect on households’ WTP for transitional energy technologies.

Hence, the final hypothesis we test is:

H₄: The WTP increases with experience with and positive beliefs about the new product.

In our context, the two transitional energy technologies somehow differ in their level of innovativeness, which plays a critical role for the behavioural factors as outlined below. The studied EEBC rather represents a continuous innovation characterized by only minor changes in either product type or existing purchasing behaviour. In contrast, the solar lighting devices share attributes of a discontinuous innovation as they involve new consumption patterns and the creation of previously unknown products (Robertson 1967 calls such a hybrid case a dynamically continuous innovation). While our study setup does not allow to derive hypotheses that link our findings to this distinctiveness of the nature of the product’s innovativeness, the behavioural factors can generally be expected to be more pronounced for a more discontinuous innovation as the solar lighting devices in our context.

3. Empirical setup


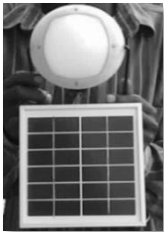


3.1. The transitional energy technologies and their returns to innovations

Transitional cooking and electricity-access technologies are exemplified by the products we offered to the participants in our studies (see Table 1). They include three types of small solar systems offered in Rwanda and an EEBC offered in Senegal: first, a portable LED lamp with an in-built battery and small solar PV panel (“Solar Kit 1” in the following). Second, a portable LED lamp that additionally provides phone or radio charging via two USB ports (Solar Kit 2); its in-built battery is recharged by connecting it to a separate solar PV panel. Solar Kit 3 is a solar home system with four LED lamps and a charging station with six USB ports powered by a larger PV panel and a larger, separate battery. The EEBC is a portable single-pot clay-metal firewood stove.

Our previous work provides rigorous evidence on the returns of both technologies. Solar kits like Solar Kit 1 lead to reductions in energy expenditures of 40% which corresponds to an annual return on investment of 19% (Grimm et al. 2017). Grimm et al. (2020) found savings potentials for each solar device shown in Table 1. In addition, it could be shown that children in households with a solar kit shifted part of their study hours into the evening and boys studied more. Finally, better quality light is likely to reduce indoor pollution and increase the value of leisure time and productivity of household activities such as cooking and light manufacturing such as the repair of clothes (Grimm et al. 2017).

For the EEBC offered in Senegal, the so-called Jambar, a randomized field study showed reductions in firewood consumption by around 30% per week and decreases in cooking duration by over 20% (Bensch and Peters 2015). In addition, the portable stove facilitates outside cooking and the cook needs to be less time in direct proximity to the cooking spot. This considerably reduces smoke exposure and is likely responsible for the decrease in self-reported respiratory disease symptoms and eye problems among women responsible for cooking (Bensch and Peters 2015). While these benefits are mostly non-monetary in the rural context where households tend to collect firewood for free, an EEBC disseminated in urban Burkina Faso, for example, turned out to pay off already after three months for more than two-thirds of the population (Bensch et al. 2015).

Table 1: Specifications of transitional energy technologies offered in this study

	Solar Kit 1	Solar Kit 2	Solar Kit 3	EEBC
				
<i>Model</i>	d.light Design S 2	Greenlight Planet Sun King Pro 2	ASE 20W Solar DC Lighting Kit	Jambar firewood stove
<i>Panel or pot size</i>	0.5 Wp	3.3 Wp	20 Wp	7 liters
<i>Technical product features</i>	▫ 1 LED lamp (25 lm)	▫ 1 LED lamp with 3 brightness settings (81 - 160 lm) ▫ 2 USB ports	▫ 4 LED lamps (220 lm in total) ▫ 6 USB ports ▫ separate battery of 14Ah	▫ quick cooking (~1h30 compared to over 2h for traditional stoves) ▫ wood savings (40-45% as compared to three stones)
<i>Expected lifespan</i>	3 years	6 years	4 years	2-4 years
<i>SE4ALL multi-tier classification</i>	Tier 0	Tier 1	Tier 1	unrated
<i>Approximate market price</i>	14 USD	40 USD	190 USD	8.5 - 13 USD
<i>Country</i>	Rwanda	Rwanda	Rwanda	Senegal

Notes: Wp stands for Watt peak, the peak power the solar kits can provide. Local currencies are converted to USD with official exchange rates at the time of the surveys of 100 FRW = 0.138 USD and 100 CFAF = 0.170 USD.

Sources: <https://www.lightingglobal.org>, Dassy Enterprise Rwanda, GIZ; Pictures: Brian Safari/ IB&C, Centre d'Études et de Recherche sur les Energies Renouvelables (CERER)/ Dakar.

3.2. Sample design and experimental procedure

The data used in this paper has been collected in the context of two willingness-to-pay (WTP) experiments among two random samples of in total 583 households from 34 rural localities in Rwanda and Senegal (see Table 2). The study sites are, as we argue, representative for the ultimate target regions of transitional cooking and electricity-access technologies, also in other sub-Saharan African countries. Only few households had these technologies at their disposal at baseline, for example thanks to relatives from urban areas. Less than three percent of sampled households were unwilling to participate in the study.

Household demand is elicited using a purchase offer procedure according to the Becker-DeGroot-Marschak (BDM) method. This method incentivizes truthful responses (Lusk et al. 2007) and has already been widely used in laboratory settings, but also in field experiments and developing countries to elicit consumer preferences (Wertenbroch and Skiera 2002; Homburg et al. 2005; Berry et al. 2020). If the bidder overstated her real reservation price, she

would have to buy the product at a price higher than her actual valuation. In contrast, by understating her real reservation price she might miss a purchase opportunity at a price that is less or equal to her valuation. Another useful feature of BDM is that it allows separating bids from market price and thereby yields higher-resolution data on households' WTP as compared to take-it-or-leave-it approaches, which provide only WTP bounds.

Table 2: Key data on the study populations and data collections

	Rwanda	Senegal
General study population	Rural communities across Rwanda	Rural villages in Peanut Basin region in central Senegal, a major agricultural region
Study site selection criteria	Appropriate levels of solar radiation; grid connection not foreseen	Ecological zone; population size; main livelihood activities; infrastructure availability; absence of access to EEBC
Study sample	323 households in 16 communities	260 households in 18 villages ²
Date of data collection	August until November 2015	November and December 2015
Implementation partners	Rwanda Energy Group (REG), Rwanda's public energy agency, and Dassy, a Kigali-based company that markets solar products	EEBC program Foyers Améliorés aux Sénégal (FASEN) implemented by the Government of Senegal and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)
References for data description	Grimm et al. (2020)	Bensch and Peters (2015, 2020)

Each household was informed in advance about a visit of a solar or stove seller that was combined with a survey on energy use; the person responsible for taking financial decisions in the household was requested to be present. Enumerators were trained as sales agents. In Rwanda, they offered the three solar kits separately, starting with Solar Kit 1 and ending with Solar Kit 3. After advertising the first product, the field team introduced the BDM purchase offer procedure to each participant followed by a hypothetical practice round without real purchase for a different product (a mobile phone in Rwanda and a solar lantern in Senegal). In general, the procedure was well understood. Rwandan participants were additionally informed about a payment period granted for the offered solar products, which was experimentally varied between one week, six weeks and five months. All participants were then asked to state their WTP for the first product, knowing that the price would be

² The Senegal sample originally also included households from the treatment group of an RCT conducted six years before the WTP experiment, to which the Jambar stove was allocated at zero price. Those treatment households are excluded from the present study, since previous EEBC ownership through the randomization likely interacts with many of the factors we assess in this study. We thereby restrict our sample to households who lived without access to the new technology at the time of the WTP experiment.

randomly drawn in public only after bidding. Before bidding for the second and third product, participants in Rwanda had to decide which product they would buy in case that two or three of the submitted bids exceeded the drawn prices. This ensured independency of the different bids, i.e. participants did not need to bother about having to spend their available budget over multiple products. In Rwanda, participants were moreover informed about the minimum and maximum prices in the draw given that answering a non-anchored WTP question for a completely new product can be cognitively challenging (Gregory et al. 1993).³

The price draw for each product was done the same day after the household visits were completed in an open community meeting in the presence of all participants. Those participants whose bids exceeded the drawn price received the product the same day and signed a binding sales contract. Payments beyond a voluntary advance payment could be made via mobile banking (Rwanda) or with the village chief (Senegal). The sample composition according to the households' WTP participation, bidding and payment behaviour can be taken from Table A1 in the Annex.

After bidding for all products and before the price draw, a structured questionnaire was administered asking questions on the socio-demographic and socio-economic status, and on the behavioural factors used to construct the various indicators used in our analysis. They are summarized in Table 3 and described in more detail in Appendix B.

3.3. Estimation framework

The empirical analysis seeks to identify behavioural factors associated with purchase decisions based on the bids households made for the transitional energy technologies offered in the two studies in Rwanda and Senegal. A substantive econometric issue arises in that some households were – understandably – not willing to bid for each product, especially not for the most expensive Solar Kit 3. A considerable share of 45% of sampled households in Rwanda did not bid for this product, probably because they considered it to be beyond their financial reach. Still, also for the smaller solar kits, a few households did not participate,

³ The minimum prices in the draw were set at approximately 30% of the market prices for Solar Kit 1 and Solar Kit 2 and 65% of the market price for Solar Kit 3. Maximum prices were the respective market prices. In Senegal, the real-purchase offer additionally included a second EEBC, and the offers for the two EEBCs proceeded in the same stepwise manner as described for the three Solar Kits in Rwanda. Since this procedure guaranteed that bids were independent and since results for the second EEBC are broadly in line with those for the Jambar presented here, we focus on the Jambar and related results.

which was not the case in Senegal. For Senegal, we therefore apply Ordinary Least Squares (OLS) estimations, whereas we choose a Tobit-type model for the Solar Kit bids in Rwanda. Bushway et al. (2007) propose this class of model estimators for cases where the decisions on whether to participate and on the bid amount are done in an integrated manner. This holds true for the Rwandan purchase offers, since households were informed about the minimum price in the draws. Thus, the WTP of non-bidders can be interpreted as lying below the respective minimum price. To account for this censoring and for the fact that some bidding households submitted bids below the minimum price, we apply an interval data model, which is a generalization of the Tobit model where censoring and interval ranges can be defined for each observation individually (Cameron and Huppert 1989).

Table 3: Alternative determinants of technology adoption and their operationalisation

Hypo-theses	Behavioural determinants of technology adoption	Operationalisation	Range	Mean (sd)	
				Rwanda	Senegal
<i>H₁ / H₂ Risk aversion and consumer resistance</i>					
	Self-assessed inclination to adopt new technologies	<i>Likert scale from 1 (least inclined) to 4 (most inclined to adopt new technologies)</i>	1-4	2.86 (0.90)	3.62 (0.60)
	Inclination to take investment risks	<i>Share of 100 USD invested in a business with 50% success rate</i>	0-1	0.64 (0.24)	0.70 (0.26)
	Acceptance of income gamble	<i>Interviewee prefers income gamble with 30 [7.5] USD in case of winning [losing] (=1) to fixed payment of 15 USD (=0)</i>	0-1	0.26 (0.44)	0.71 (0.45)
	Early adoption measure	<i>Number of most recent technologies adopted by household (up to three)</i>	0-3	1.22 (0.97)	0.81 (0.78)
	Index of low innovation resistance	<i>Normalized sum of four innovation resistance questions on a scale from 1 to 5 each, derived only for those households that did not yet adopt the introduced technology</i>	0-1	0.66 (0.12)	0.60 (0.13)
<i>H₃ Time preferences</i>					
	Preference for the present	<i>Interviewee prefers lower instant (=1) to higher later (=0) payment (5 USD today vs. 15 USD in one month)</i>	0-1	0.71 (0.46)	0.54 (0.50)
<i>H₄ Experience and beliefs</i>					
	New-technology experience	<i>Experience with the introduced technology</i>			
		<i>unknown</i>		0.13	0.09
		<i>heard before</i>	0-1	0.65	0.58
		<i>owned or used before</i>		0.12	0.21
		<i>currently owning</i>		0.10	0.12
	Expected lifetime	<i>Ratio of interviewee's expected lifetime to the lifetime indicated by product supplier</i>	>0	–	1.42 (1.29)

Note: sd refers to the standard deviation. Expected lifetime has been elicited for Senegal only. For the Senegal data, 37 and 20 “don’t know” answers are excluded for *self-assessed inclination to adopt new technologies* and *expected lifetime*, respectively.

We regress the individual bids Y of households i from community j separately on each of the behavioural, individual-specific factors Z_i described in Table 3. In all estimations, bids are log-transformed such that the estimated coefficients can be interpreted as elasticities or semi-elasticities. Furthermore, all estimations include village dummies v_j and an unobserved household-specific residual, ϵ_{ij} . Accordingly, our main estimations are

$$\ln(Y_{ij}) = \alpha_0 + \alpha_1 Z_{ij} + v_j + \epsilon_{ij} \quad (1a), \quad \ln(Y_{ij}) = \alpha_0 + \alpha_1 Z_{ij} + X'_{ij} \alpha_2 + v_j + \epsilon_{ij} \quad (1b),$$

once without (1a) and once with (1b) a vector of further explanatory variables X'_i . The main coefficient of interest is α_1 , the coefficient for the behavioural variables Z_i . As base regressions, we additionally estimate equation (1b) without Z_i , thus include only the non-behavioural explanatory variables.

X'_i covers several socio-demographic household characteristics and proxies for household wealth and income that are potentially important in the adoption of the concerned new technologies. They include household size (in natural log (ln)), the household head's education as well as gender and whether s/he is a subsistence farmer. Building materials of the house and vehicle ownership are included to control for household's wealth. We control for income through household expenditures that exclude expenditures on energy. We also include the age difference between the enumerator and respondent, since studies have shown the household head's age to be an important predictor of technology adoption and since the specific interview situation may influence response behaviour. Estimations using data from Rwanda additionally involve controls for the randomly assigned payment period. Descriptive statistics on these control variables can be taken from Table A2 in the Annex, which underpin that living standards differ across the two countries despite similarities of the context. For example, household sizes and expenditure levels are by far larger in Senegal, whereas formal education is clearly higher in Rwanda.

4. Results

4.1. Base regressions

Table 4 presents results for base regressions that only include the non-behavioural explanatory variables. This gives an idea on how bidding is generally correlated with the characteristics that are subsequently used as control variables. Table 4 shows that our control

variables do not explain much of the variance in the elicited WTP. Correlations are largest in size for Solar Kit 3. Still, even these correlations are rather weak, for example for household size. Formal education is a positive predictor for higher bids only in Rwanda, which may be due to the informal religious education common among older household heads in Senegal. Despite cooking being a household chore for women in the two countries, female-headed households are not more inclined to submit higher bids for cooking stoves.

Table 4: Base regressions without technology adoption determinants

dependent variable	Bid amount for the respective product in USD (ln)							
	country		Rwanda				Senegal	
	product		Solar Kit 1		Solar Kit 2		Solar Kit 3	
	estimation		Interval Reg		Interval Reg		Interval Reg	
	with controls		no	yes	no	yes	no	yes
Household size (ln)			-0.002 (0.05)		-0.01 (0.07)		0.11 (0.11)	-0.04 (0.06)
Household head attended at least primary school			0.02 (0.05)		0.03 (0.06)		0.05 (0.09)	-0.09 (0.08)
Household head is female			0.002 (0.06)		-0.09 (0.08)		0.05 (0.13)	0.01 (0.10)
Household head's main occupation is farming			0.08 (0.06)		-0.04 (0.06)		0.02 (0.12)	0.002 (0.09)
Flooring material is cement or tiles			0.000 (0.07)		-0.10 (0.07)		0.13 (0.14)	0.001 (0.08)
Wall material is stone or brick			0.02 (0.06)		0.07 (0.09)		-0.04 (0.12)	-0.01 (0.08)
Vehicle ownership (incl. bicycles)			-0.04 (0.05)		0.05 (0.07)		0.34*** (0.11)	-0.08 (0.07)
Monthly household expenditures (ln)			0.01 (0.02)		0.11*** (0.03)		-0.05 (0.05)	0.06 (0.06)
Age difference between enumerator and respondent (yrs)			-0.005*** (0.002)		-0.002 (0.002)		-0.01*** (0.00)	-0.01*** (0.003)
Payment period								
1-week payment period			Reference		Reference		Reference	
6-weeks payment period			0.04 (0.06)	0.01 (0.06)	0.03 (0.07)	-0.01 (0.07)	0.16 (0.12)	0.05 (0.13)
5-months payment period			0.14** (0.06)	0.12** (0.06)	0.10 (0.07)	0.08 (0.07)	0.12 (0.12)	0.06 (0.13)
Village dummies			yes	yes	yes	Yes	yes	yes
Adjusted R-squared			—	—	—	—	—	0.00
Number of observations			323	321	323	321	323	254
Average WTP in USD (sd)			5.27 (2.21)		18.05 (7.69)		100.37 (48.49)	11.74 (7.16)

Notes: sd refers to the standard deviation; robust standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01.

Wealth indicators and expenditure levels as an income proxy, unsurprisingly, show some but not a too strong correlation with the two larger, more expensive solar kits, whereas no pattern can be observed in Senegal for cooking stoves. A larger age difference between sales agent and potential buyer mostly affects bidding negatively. Lastly, the longer payment periods granted to respondents seem to have the most robust effect for the small Solar Kit 1, which may hint to the disproportionately strong liquidity constraints among those most interested in these small systems.

4.2. Main results

We now turn to Table 5 with results for the different potential behavioural technology adoption determinants. Again, the table presents specifications without and with the control variables from Table 4. Each set of results for the individual variables refers to separate estimations. The five first measures presented in the table refer to the behavioural dimension *Risk aversion and consumer resistance*. The self-assessment of households regarding their *inclination to adopt new technologies* and the *inclination to take investment risks* both strongly correlate with the measured WTP for the discontinuous innovation, the solar kits. This differs from the EEBC in Senegal, for which these behavioural aspects play a minor role in the uptake decision. The significant coefficients imply, for example, that a one-level increase in the four-level Likert scale on new technology adoption goes along with a 10 to 29% higher bid for the individual solar kits. Remember that respondents did not yet know whether they had successfully bid for the solar kit or cooking stove when answering to the structured questionnaire. Hence, the reporting of a high inclination to adopt new technologies cannot just be a reflection of a successful bid.

The even more pronounced correlations for *inclination to take investment risks* do not necessarily imply that households willing to invest in these products are more prone to take risks per se: we find rather little evidence that the inclination to adopt the new technology increases with a higher *acceptance of an income gamble*, i.e. for households with a preference for a potentially higher but more uncertain payout over a fixed payout with identical expected value. Overall, we conclude that the data rather supports our first hypothesis H_1 : The WTP decreases with risk aversion, i.e. increases with risk tolerance. This effect is, furthermore, more pronounced with the discontinuous innovation than with the continuous innovation.

Table 5: Estimation results for the different technology adoption determinants

dependent variable	Bid amount in USD (ln)							
	country		Rwanda				Senegal	
	product		Solar Kit 1		Solar Kit 2		Solar Kit 3	
	estimation		Interval Reg		Interval Reg		Interval Reg	
with controls	no	yes	no	yes	no	yes	no	yes
Self-assessed inclination to adopt new technologies								
Coefficient	0.13***	0.10***	0.20***	0.16***	0.29***	0.25***	0.04	0.07
SE	(0.02)	(0.02)	(0.03)	(0.03)	(0.05)	(0.05)	(0.05)	(0.06)
$p > z $	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.44]	[0.25]
Inclination to take investment risks								
Coefficient	0.21**	0.25**	0.29***	0.23**	0.68***	0.65***	0.10	-0.02
SE	(0.10)	(0.10)	(0.11)	(0.11)	(0.20)	(0.21)	(0.12)	(0.13)
$p > z $	[0.04]	[0.02]	[0.01]	[0.04]	[0.00]	[0.00]	[0.42]	[0.90]
Acceptance of income gamble								
Coefficient	0.01	0.02	0.11*	0.09	0.02	0.05	0.01	0.04
SE	(0.05)	(0.05)	(0.06)	(0.06)	(0.10)	(0.11)	(0.07)	(0.06)
$p > z $	[0.78]	[0.69]	[0.08]	[0.16]	[0.81]	[0.66]	[0.89]	[0.54]
Early adoption measure								
Coefficient	0.06**	0.03	0.13***	0.10***	0.24***	0.23***	0.09**	0.09*
SE	(0.03)	(0.03)	(0.03)	(0.03)	(0.05)	(0.05)	(0.04)	(0.05)
$p > z $	[0.01]	[0.25]	[0.00]	[0.00]	[0.00]	[0.00]	[0.04]	[0.06]
Index of low innovation resistance								
Coefficient	-0.05	0.07	0.34	0.34	-0.24	-0.24	0.46	0.63**
SE	(0.21)	(0.21)	(0.26)	(0.26)	(0.43)	(0.42)	(0.29)	(0.27)
$p > z $	[0.81]	[0.73]	[0.18]	[0.20]	[0.57]	[0.57]	[0.10]	[0.02]
Preference for the present								
Coefficient	0.02	-0.01	0.07	0.06	-0.11	-0.15	-0.01	0.002
SE	(0.05)	(0.05)	(0.07)	(0.06)	(0.11)	(0.10)	(0.07)	(0.07)
$p > z $	[0.65]	[0.86]	[0.31]	[0.29]	[0.31]	[0.13]	[0.89]	[0.97]
New-technology experience								
<i>unknown</i>	<i>Reference</i>		<i>Reference</i>		<i>Reference</i>		<i>Reference</i>	
<i>heard before</i>								
Coefficient	0.09	0.08	0.21*	0.16	0.37**	0.36*	0.13	-0.02
SE	(0.08)	(0.08)	(0.11)	(0.11)	(0.19)	(0.20)	(0.15)	(0.16)
$p > z $	[0.25]	[0.33]	[0.06]	[0.13]	[0.05]	[0.07]	[0.38]	[0.88]
<i>owned or used before</i>								
Coefficient	0.10	0.01	0.28**	0.12	0.61***	0.51**	0.17	0.03
SE	(0.10)	(0.10)	(0.12)	(0.12)	(0.20)	(0.22)	(0.16)	(0.17)
$p > z $	[0.32]	[0.89]	[0.02]	[0.32]	[0.00]	[0.02]	[0.29]	[0.87]
<i>currently owning</i>								
Coefficient	0.04	0.08	-0.07	-0.03	0.26	0.18	-0.16	0.10
SE	(0.10)	(0.11)	(0.14)	(0.13)	(0.24)	(0.24)	(0.18)	(0.20)
$p > z $	[0.66]	[0.49]	[0.60]	[0.80]	[0.28]	[0.45]	[0.38]	[0.63]
<i>joint significance[‡]</i>								
Prob > F	[0.66]	[0.70]	[0.00]	[0.12]	[0.01]	[0.09]	[0.06]	[0.84]

Table continues next page

Table continued

	Solar Kit 1		Solar Kit 2		Solar Kit 3		EEBC	
	Interval Reg		Interval Reg		Interval Reg		OLS	
	no	yes	no	yes	no	yes	no	yes
Expected lifetime								
Coefficient		–		–		–	0.06	0.05
SE							(0.04)	(0.05)
$p > z $							[0.12]	[0.33]
Adjusted R-squared	–	–	–	–	–	–	.00 -	.06 -
							.07	.11
Number of observations	323	321	323	321	323	321	257	252

Notes: [†] A Wald test is performed to test the joint significance of the three attributes *heard before*, *owned or used before*, and *currently owning*. Robust standard errors in parentheses and p -values in squared brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The *early adoption measure* is the only measure for which we find a significant positive correlation for all four assessed products. The coefficients in Table 5 suggest that early adoption of other new technologies goes along with an up to 24% higher WTP. Looking closer into this measure exposes the dearth of new technologies available to the rural households: they are mostly confined to new fertilizers, agricultural techniques and mobile money, apart from cooking stoves or solar technologies. Similarly, little variation could be observed for the *index of low innovation resistance* (see also Table 3). People are mostly open to new technologies, but hesitant in that the large majority prefers to wait for technology advancements. Still, we find that a less pronounced innovation resistance is positively associated with WTP in the cooking stove sample. Overall, we find support for our hypothesis H_2 – lower innovation resistance tends to be associated with higher WTP.

The factor *preference for the present* delivers small and imprecise estimates, which may be due to its ambiguous nature in our context: as noted above, a higher preference for the present is generally a barrier to adoption since longer-term benefits are discounted more strongly. Yet, in our setup, people immediately received the product, whereas payment only took place later. This created some incentive for people with a higher preference for the present to purchase the products. We see this when introducing interaction terms between time preference and payment periods in our estimations for Rwanda (not shown in the table): the pure time preference effect becomes negative in all estimations, whereas the interaction terms with longer payment periods show positive (though not statistically significant) coefficients. Hence, there is only weak and imprecise evidence related to our hypothesis H_3 on the relationship between WTP and a preference for the present.

Testing the effect of any *past experience with the new technology* is insightful as people may have heard both positively and negatively about the products. Significant or at least borderline significant effects (p -values between 0.05 and 0.13) can only be observed for the two larger Solar Kits 2 and 3. The coefficient for *currently owning* the respective device is also presented for the sake of completeness. However, it is not comparable since it rather reflects the WTP for an additional product of the new device type. To conclude, the results support the hypothesis H_4 , where we put forward that WTP generally increases with knowledge about and experience with a new (quality) product and that this relationship is stronger for the more complex discontinuous innovation.

Finally, the *expected lifetime*, which has only been elicited for Senegal, has a significant effect on the individuals' WTP. Yet, the size of the effect seems fairly modest: the coefficients can be interpreted in a way that the WTP of someone who expects the cooking stove's lifetime to exceed its general lifetime by 50% has a WTP that is about 5% higher than the WTP of someone who expects the cooking stove to fall apart when merely half of the general lifetime has elapsed. Hence, this suggests that consumers align their WTP with the expected usage period of the investment.

Overall, we see stronger associations for the small solar systems, potentially because they share more attributes of a discontinuous innovation. We cannot exclude that the absence of significant associations is partly due to insufficient statistical power, but estimates suggest that the picture would not deviate substantively if more data was available. Our results substantiate the relevance of behavioural factors to understand the demand for innovative consumer durables. Behavioural factors have a moderate effect on people's absolute WTP. Similar to fundamental socio-demographic factors such as the educational level or the main occupation of the household head, they cannot explain large parts of the variation in WTP. Yet, they contribute significantly to the overall decision process and hence constitute an important piece of information for potential suppliers on these markets.

5. Conclusion

Elaborating effective policy designs and marketing strategies for the distribution of new technologies in BoP markets requires to understand the interplay between behaviour, market settings, traditional institutions and technology payoffs simultaneously. When the

advantages and disadvantages of a technology are not easily observed or understood, BoP consumers are particularly sensitive to factual information and credible knowledge about the technologies that are offered to them. BoP consumers tend to be risk averse and rather tend to wait until a new technology has made its inroads into their communities. Our results suggest that policy designs and marketing strategies might be more successful if they target the least risk-averse households as they demonstrate a higher willingness to pay and tend to adopt earlier. These 'early-adopters' may then help to spread the information about new technologies in their communities. In this context marketing strategies may also work better if they provide information about the potential returns and the expected usage period, as we could show for the EEBC. Similarly, it seems important to design subsidy schemes, which seem required to achieve the goals of universal access to affordable and clean energy laid out in the Sustainable Development Goal 7, in a way that is informed by the behavioural insights from this study. Interestingly our results show that the self-assessed inclination to adopt new technologies are particularly important for the small solar devices, but in turn do not explain much in the uptake of EEBCs. EEBCs are clearly not as complex as solar lamps, which may explain the difference in the role of behavioural patterns observed across both products.

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Appendix A

Table A1: WTP participation, bidding and payment behaviour of households

	Number of households	
	Rwanda	Senegal
Not willing to participate	12	4
WTP below prices drawn	129	52
Purchase withdrawn before contract signing	28	4
Product bought and paid fully	102	93
	<i>Kit 1: 50; Kit 2: 50; Kit 3: 2</i> <i>another 103 purchases of the second EEBC</i>	
Product not paid fully	52	4
Total	323	260

Table A2: Descriptive statistics on main household characteristics used as control variables

	Rwanda		Senegal	
	mean	sd	mean	sd
Household size	4.53	1.73	13.46	9.07
Household head attended at least primary school	0.65		0.33	
Household head is female	0.19		0.14	
Household head's main occupation is farming	0.80		0.87	
Flooring material is cement or tiles	0.20		0.61	
Wall material is stone or brick	0.69		0.34	
Vehicle ownership (incl. bicycles)	0.26		0.36	
Monthly household expenditures (excl. expenditures on energy), in USD	53.29	61.40	228.06	171.17
Absolute age difference between enumerator and respondent	15.17	13.44	17.26	12.72
Number of observations	323		260	

Note: sd refers to the standard deviation; the number of missings per variable does not exceed one in Rwanda and six in Senegal after few control variable values were imputed econometrically or otherwise based on other survey information (*Household size* and *Household head attended at least primary school* (each 2 in Senegal); *Absolute age difference* (27 in Senegal); *Monthly household expenditures* (12 in Rwanda))

Appendix B: Measurement of Variables

Risk aversion and consumer resistance. To avoid the ambiguity introduced by relative riskiness of old and new technologies (cf. Section 2), we concentrate on eliciting the perceived riskiness of the new technology. Specifically, we measure risk aversion in three ways: First, following Giné and Yang (2009), we asked respondents to self-report on a Likert scale to what degree they are ready to take risks in purchasing new products. The scale ranged from 1 to 7 in Rwanda and from 1 to 5 in Senegal. Second, we played an investment game in which each respondent is put in a hypothetical situation of winning about 100 USD that can be invested into a business or not.¹ The invested amount would either double or halve, both with the same ex-ante probability. Given this payout pattern, respondents had to decide how much to invest of the 100 USD. Third, in an income gamble adapted from Barsky et al. (1997), the participant was asked to imagine s/he had approximately 15 USD and is then invited up to three times to either keep the money or to gamble. The odds to win the gamble as well as the winning amount are held constant across all three attempts at 0.5 and roughly 30 USD, respectively. Yet, the loss s/he incurs in case of losing decreases approximately from 7.5 USD to 5 USD to 3 USD. The earlier the participant accepts the gamble, the more s/he is accepting risks.

To capture consumer resistance, we follow Levine et al. (2018) and construct an early-technology adopter measure for which respondents are asked to list the three most recent technologies that others in the community had bought and whether they adopted any of these technologies, which gives us an ordinal measure from zero to three. Improved cooking stoves or solar technologies could only be mentioned in the country where they were not the technology introduced in the WTP experiment, as their adoption would otherwise fall under the *experience* dimension. To approximate the physical, economic, functional and social risk that people associate with new technologies, we adjust Ram's (1989) *Measures of Innovation Resistance*. We asked respondents to rate their accordance with four statements on a scale from 1 to 5 (where 1= totally agree, 3= no opinion, 5=totally disagree). Perceived social risk or habit are captured by the statement "*In my village we have always lived well without this technology*", functional risk by "*For me and my family, it would be difficult to get used to solar kits/ improved stoves*", perceived physical risk by "*Solar kits/ improved stoves can be dangerous*", and economic risk by "*There will soon be a technology available that is better than this type of solar kits/ improved stoves, for instance the national grid*".

¹ 100 USD are equivalent to about one (three) month of average wage for casual agricultural work in the Senegalese (Rwandan) study area (Bensch and Peters 2020; Jones et al. 2022). Similarly, the amount is about half (twice) the average household expenditure in our Senegalese (Rwandan) sample (see Table A2).

Time preference. We concentrate on the measurement of discount factors, abstracting from hyperbolic preferences, which are far from trivial to identify (Mahajan et al. 2020). The literature typically uses intertemporal choice questions to approximate discount rates. We included three questions in our survey where each requires making a choice between getting a present from a trusted person of about 5 USD today and about 15 USD alternatively in two weeks, one month, in three months or in one year (see as well Levine et al. 2018). A respondent with a strong preference for today's consumption and thus a high discount rate would choose receiving the gift today even in the case of a two-week delay.² We define a bidder as having a low discount rate if the bidder chooses 15 USD in each situation.

Experience and beliefs. To test the role of product experience, we asked households whether they ever had or still have a comparable device. Moreover, we asked households whether they had used or seen such a device in someone else's household, or whether they have heard about it. Two questions measured the respondents' expectations about the benefits associated with the new technologies. First, whether they think the device will reduce their energy expenditures, second, which lifetime people think the device will have (the latter was only asked to interviewees in Senegal). The belief indicator on whether households expect the device to reduce energy expenditures is not shown in the results section because virtually all interviewees responded with 'yes'.

Additional references

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² The amounts are chosen such that differences between them exceed local lending interest rates, which households could earn by taking the earlier payout. Taking the earlier payout hence reflects not only the time value of money but also time preference.