Environment for Development

Discussion Paper Series November 2017 ■ EfD DP 17-15

Demand for Off-Grid Solar Electricity

Experimental Evidence from Rwanda

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Demand for Off-Grid Solar Electricity: Experimental Evidence from Rwanda

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Abstract

The cost of providing electricity to the unconnected 1.1 billion people in developing countries is significant. High hopes are pinned on market-based dissemination of off-grid technologies to complement the expensive extension of public grid infrastructure. In this paper, we elicit the revealed willingness-to-pay for different off-grid solar technologies in a field experiment in rural Rwanda. Our findings show that households are willing to dedicate substantial parts of their budget to electricity, but not enough to reach cost-covering prices. Randomly assigned payment periods do not alter this finding. We interpret the results from two perspectives. First, we examine whether the United Nations' universal energy access goal can be reached via unsubsidized markets. Second, in a stylized welfare cost-benefit analysis, we compare a subsidization policy for off-grid solar electrification to a grid extension policy. Our findings suggest that, for most of rural Africa, off-grid solar is the preferable technology to reach mass electrification, and that grid infrastructure should concentrate on selected prosperous regions.

Key Words: public infrastructure, technology adoption, electrification, willingness-to-pay, energy access

JEL Codes: D12, H54, O13, Q28, Q41

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1. Introduction

Universal electricity access is a primary goal of the international community. The Sustainable Development Goals (SDG) and the United Nations' initiative 'Sustainable Energy for All' (SE4All) call for connecting the 1.1 billion people worldwide hitherto lacking electricity access by 2030. Yet, the contribution of electricity to economic development is unclear. It is beyond discussion that the economic transition in industrialized countries would not have been possible without electrification. However, the right timing of electrification in developing countries, particularly in remote and sparsely populated areas, is under debate, given modest short-term impacts and high investment costs. For Asian and Latin American countries, Lipscomb et al. (2013), Rud (2012), van de Walle et al. (2016), and Khandker et al. (2013) find positive effects on various socio-economic outcomes. For Africa, in contrast, it is less clear whether electrification triggers massive economic development (Bernard 2012; Chaplin et al. 2017; Dinkelman 2011; Lenz et al. 2017; Peters and Sievert 2016). At the same time, the cost of electrification is substantial. OECD/IEA estimates that, for Africa alone, the investment requirements to achieve universal access by 2030 are at 19 billion USD

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Acknowledgements: Data collection underlying this research was financially supported by the Centre for Development Research in Bonn (ZEF) and the Federal Ministry for Economic Cooperation and Development (BMZ). Lenz, Peters, and Sievert gratefully acknowledge the support of a special grant (Sondertatbestand) from the German Federal Ministry for Economic Affairs and Energy and the Ministry of Innovation, Science, and Research of the State of North Rhine-Westphalia. The authors thank Anicet Munyehirwe and IB&C Rwanda for the implementation of the field work. Cyndi Berck, Chiara Kofol, Frank Otchere, and Ferdinand Rauch, as well as participants at the Environment for Development (EfD) annual meeting in Shanghai, the Sustainable Energy Transition Initiative (SETI) annual meeting at Duke University, the CSAE Conference in Oxford, and research seminar participants at the World Bank Development Research Group seminar in Washngton D.C., at University of the Witwatersrand in Johannesburg, ETH Zurich, University of Göttingen, University of Marburg, University of Groningen, Erasmus University Rotterdam, the ZEF Bonn and the Development Network Berlin workshop provided valuable comments and suggestions. All correspondence to: Jörg Peters, RWI, Hohenzollenstraße 1-3, 45128 Essen, Germany, e-mail: peters@rwi-essen.de, phone: ++49-201-8149-237.

annually (IEA 2011; World Development Indicators 2014), which corresponds to almost 45 percent of the yearly official development assistance influx to the continent.

Only recently, researchers have started questioning whether public funds should be used to subsidize mass electrification. Especially in developing countries, the tight governmental budgets are up against various underfinanced public services, such as transport, health and education infrastructure, and thus opportunity costs are high. This is prominently illustrated by Lee et al. (2016), who randomized different connection fees across villages in Western Kenya to obtain households' revealed Willingness-to-Pay (WTP) for grid access. Because the WTP they observe covers only a small part of the required cost, they suggest that electrification creates a 'welfare loss' ranging between 540 and 1,100 USD per household. Lee et al. (2016) acknowledge that a revealed WTP is constrained in a context of imperfect capital markets, as people cannot easily access credit to finance connection costs. Moreover, it is likely that a revealed WTP reflects only internalized benefits. Yet, the authors implicitly argue that non-internalized private and social benefits are unlikely to justify subsidies on this order of magnitude.

In the present paper, we complement Lee et al. (2016) by studying the revealed WTP for three different *off-grid* solar technologies. SE4All as well as the SDGs include off-grid solar as one pillar of their multi-tier definition of modern energy. While Lee et al. (2016) provide novel insights on the demand for electrification at the upper bound of the technological spectrum, the present paper is to the best of our knowledge the first to study demand for electrification at the lower bound.

Investment costs for the devices we offered vary between 13 and 182 USD. Unlike on-grid electrification, off-grid electricity does not require large-scale infrastructure investments, including power plants and transmission lines. At the same time, service levels are lower for off-grid than for on-grid connections. The solar kits used in this paper allow for different energy usage levels starting from just one task light to several lighting sources, mobile phone charging, and radio usage. They cannot power high-wattage appliances like machinery, electric stoves, fridges, or irons.[1] This can become a bottleneck for productivity development in some places. Even in grid-covered areas, though, demand patterns in many parts of rural Africa can also be fulfilled by off-

[1] For the sake of clarity, we ignore decentralized mini-grids that are powered by solar, wind, hydro, or diesel generators. Depending on their scale, they allow for higher power services, but incur high upfront investment costs for distribution lines as well as generation and storage capacities. Our argument is robust to the inclusion of mini-grids, since their cost structure is similar to the Lee et al. (2016) cost estimates, which include only transformers and distribution lines.

grid solar, because electricity is virtually never used for cooking or refrigeration in households, and because machinery usage in enterprises is also very rare (see, for example, Chaplin et al. 2017; Lenz et al. 2017; and Peters et al. 2011).

Using a sample of 324 randomly selected households in 16 remote and poor off-grid communities spread across rural Rwanda, we elicit the WTP for three different types of off-grid solar – a 0.5 Watt, a 3.3 Watt, and a 20 Watt device – using a Becker-DeGroot-Marschak real-purchase offer bidding game. In addition, each household was randomly assigned to a payment period of seven days, six weeks, or five months in order to test for the effect of a zero-interest rate credit scheme on the WTP.

We find that the average WTP for the three solar kits is between 38 and 55 percent of their respective market prices. Even at the upper tail of the income distribution, few households are able and willing to pay amounts that come close to the market prices. This observation is in line with the broader literature on the adoption of socially desirable technologies. In recent years, many studies have shown, in particular for health-relevant products, that demand is highly price elastic (see Cohen and Dupas 2010; Dupas 2014; Tarozzi et al. 2014; Kremer and Miguel 2007; Mobarak et al. 2012). The similarity between these technologies and electricity is that benefits are not fully internalized and policy therefore intervenes to facilitate adoption. This branch of literature strongly advocates 'cost-sharing' dissemination strategies, i.e., subsidized end-user prices to bring adoption rates to a socially desirable level (Bates et al. 2012).

SE4All and most programs that subscribe to it pursue a market-based paradigm, expecting the target group to pay cost-covering prices for off-grid solar technologies. While the affordability problems of the poor are well known, the hypothesis is typically that people's WTP is high enough but is constrained by a lack of liquidity. However, we find that relaxing this liquidity constraint from a seven-day payment period to either six weeks or five months increases the WTP for any of the kits by 12 percent at most. Accounting for interest rates that are typically high in rural areas shows that this increase in WTP is not enough to cover capital costs and overheads that would be associated with a credit-based financing scheme. We thereby also contribute to the literature on liquidity constraints and technology adoption in poor settings (see, for example, Beltramo et al. 2015, Yishay et al. 2016, Devoto et al. 2012, Tarozzi et al. 2014, and Yoon et al. 2016).

We then interpret our findings from two perspectives. In the *SE4All angle*, we examine whether households in poor and remote areas – a considerable part of the 1.1 billion without electricity – can afford to pay cost-covering prices for off-grid solar. In the *Social Planner's angle*, we ask whether a full subsidization policy would be desirable from a welfare-oriented public policy perspective.

Our findings in the *SE4All angle* suggest that the vast majority of the rural poor will not be able to pay cost-covering prices for off-grid solar technologies. The United Nations' SE4All initiative and the World Bank's Lighting Global platform, the flagship program for off-grid solar energy, promote the distribution of off-grid electricity without end-user subsidies through the private market (see Lighting Global 2016). M-Kopa and d.light are two examples of successful solar companies with high sales numbers in Kenya, Tanzania, and Ethiopia (Lighting Global 2016). Our findings do not challenge the approaches of these pioneers in certain better-off strata of those countries, but emphasize that market-based approaches will have difficulties in reaching the poorer populations in rural Africa and, correspondingly, the SE4All goal of universal electricity access.

In the *Social Planner's angle*, we conduct a back-of-the-envelope welfare assessment of a subsidization policy. We find that the internalized benefits, as reflected in the WTP, do not cover the costs of off-grid solar electrification and hence subsidization leaves an *internal return on investment gap*. The gaps range between 8 and 85 USD per household for the different technologies and are considerably lower than what Lee et al. (2016) observed for on-grid electrification. In a next step, we discuss the benefits of off-grid solar electricity that might not be reflected in WTP, most notably long-term benefits and external effects. From a welfare perspective, a full subsidization would be justified if these benefits are high enough to close the *internal return on investment gap*. We provide a brief review of the literature and show that the evidence on the effects of small off-grid solar is generally positive, yet there is no indication for a transformative development effect. Nonetheless, although external effects of off-grid solar are certainly lower than for on-grid electricity in absolute terms, in relative terms they are likely to cover larger parts of the *internal return on investment gap*, due to the high cost of grid extension. We therefore conclude that, if mass electrification is a political goal, off-grid solar is the preferable technology for large parts of rural and poor Africa. At least for the next two decades, high-cost grid infrastructure investments should concentrate on selected prosperous areas with high business potential.

The remainder of the paper is structured as follows. In Section 2, we present SE4All and briefly discuss energy access policy in Africa, as well as the country background. Section 3 describes our methodological approach and our data. In Section 4, we present our main results on the WTP, on the impacts of the payment periods, and on the difficulty in collecting instalment payment. Section 5 interprets our findings from the *SE4ALL angle* and the *Social Planner's angle*. Section 6 concludes.

2. Background

2.1. Policy Background

For most African governments, grid extension is the most obvious intervention to increase access to electricity and to reach the SE4ALL goal. However, in recent years, decentralized solar technologies have gained importance as a lower-cost alternative, in particular because production costs of panels, storage systems, and LEDs have decreased considerably. Since 2009, the World Bank program 'Lighting Global' has supported the international off-grid lighting market for products of up to 10 Watts. The so-called pico-solar products promoted by this program provide different basic energy services depending on the panel size, such as lighting, radio, and mobile phone charging. Larger off-grid solar products, typically referred to as solar home systems (SHS), are additionally able to run TV sets and comparable devices, but not high-wattage devices (e.g., fridges) and appliances running on alternating current.

In the absence of electricity, people in rural Sub-Saharan Africa light their homes using traditional lighting sources – kerosene-driven wick and hurricane lamps or candles. Additionally, dry cell battery-driven LED lamps have become available in recent years in almost every rural shop and are increasingly used (see Bensch et al. 2017). Some households in rural areas resort to only the dim light emitted by the cooking fire. For many households, expenditures on kerosene and batteries constitute a considerable part of their total expenditures. This level of baseline lighting consumption is an important factor for the decision to invest in a solar kit, since it determines the replaceable expenditures and thus the cash flow expectations.

Lighting Global's approach assumes that off-grid solar products will make their way into households through the market. The program has introduced a quality verification system and supports manufacturers and retailers in overcoming information asymmetries that might prevent customers from buying the products. Credit constraints are supposed to be eased via credit and smart payment systems such as the Pay-as-you-go mechanism (PAYG), which allows customers to pay for the kit in small installments, often via mobile money. An additional innovative feature that can be combined with PAYG is to lock the solar kit remotely in case of non-payment, through an installed microchip connected to the mobile phone network. Generally, Lighting Global opposes direct end-user subsidies. According to Lighting Global (2016), around 4.3 million pico-solar kits were sold in Africa, with sales concentrating in Ethiopia, Kenya, and Tanzania. Customers so far are mostly somewhat better-off households. It is important to emphasize that, in addition to the branded and quality-verified products promoted by Lighting Global, non-quality verified (i.e., non-branded) solar products are available virtually everywhere in rural Africa (see Bensch et al. 2016; Grimm and Peters 2016; Lighting Global 2016).

The link between Lighting Global and SE4All is established by the Global Tracking Framework and its multi-tier system (SE4All 2013), which defines what type of electricity supply qualifies as modern energy. For example, a regular connection to the national grid qualifies as Tier 3 or 4, because it allows for using lighting, a television, and a fan all day. An SHS qualifies for Tier 1 or 2 depending on its capacity. Tier 1 requires providing access to a peak capacity of at least 1 Watt and basic energy services comprising a task light and a charger for radios or phones. Most solar products promoted by Lighting Global, as well as two of the three kits used in this study, qualify for Tier 1. Our smallest kit is just a tad below the Tier 1 threshold (because it includes only a lamp and lacks a phone charger; see Section 3.1.). There is a wide spread between the service qualities and costs of the different tiers; the retail price of the smallest pico-solar kit used in this study is around 13 USD.[2] For comparison, the World Bank (2009) estimates a cost range for on-grid electrification in rural areas of 730 to 1450 USD per connection, which is confirmed by Lee et al. (2016) for the case of Kenya and by Lenz et al. (2017) for Rwanda. Chaplin et al. (2017) provide evidence of how sensitive connection costs are to population density and connection rates; for Tanzania, they observe connection costs as high as 6,600 USD per household, and note that only 20 percent of households in the target region get connected.

2.2. Country Background

The Government of Rwanda sees electrification as a priority to reach its poverty reduction goals (see MININFRA 2016). Rwanda’s energy sector is undergoing an extensive transition, in which electricity provision plays a dominating role. It is the government’s objective to increase the electrification rate to 70 percent by 2018 and to full coverage by 2020. The key policy instrument is the huge *Electricity Access Roll-Out*

[2] We use the official exchange rate in April 2016 for conversion, i.e., 100 Rwandan Franc (RWF) = 0.13 USD.

Program (EARP), which increased the national connection rate from 6 to 24 percent country-wide between 2009 and 2015. While EARP Phase I relied on grid electrification only, half of the Phase II connections are scheduled to be provided via decentralized technologies (SE4All 2014), including SHS and pico-solar kits (MININFRA 2016). More recently, the so-called *Bye Bye Agatadowa* initiative has attracted some attention, with its aim of eliminating kerosene lamps completely from the country by facilitating access to pico-solar. In the African context, this engagement of the government is extraordinary. Note that the communities sampled for this study have not yet been reached by these activities and no concrete plan for electricity-related roll-out has been announced for the near future. In that respect, they resemble typical off-grid areas in Africa (see Section 3).

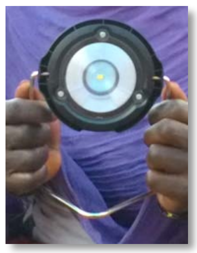
3. Research Approach and Data

We conducted a Randomized Controlled Trial (RCT) among 324 randomly selected households in 16 rural communities in Rwanda and elicited the WTP for three different solar kits using a real-purchase offer game based on the Becker-DeGroot-Marschak (BDM) mechanism. Each household was visited individually and was offered the three solar kits. It is important to emphasize that the three kits were offered sequentially, starting with Kit 1 and followed by Kit 2 and 3. For the payment, each household was randomly assigned a payment period of either one week, six weeks, or five months. This randomization of payment periods was stratified at the community level. In this section, we first briefly describe the three solar technologies that were offered, followed by the sampling process and the bidding game to elicit the WTP.

3.1. Off-Grid Technologies Offered in Bidding Game

We cooperated with a pico-solar vendor and selected three kits out of his product range that he offered in Kigali and on some rural markets. Table 1 presents the three types. The most basic kit is the *d.light S2* (“*Kit 1*”), an LED lamp with an integrated small solar panel. It provides only lighting and thus does not reach Tier 1 in the SE4ALL multi-tier metric. The second kit offered is the *Sun King Pro 2* (“*Kit 2*”), which is borderline eligible for Tier 1 because it provides lighting and phone or radio charging via two USB ports. Kits 1 and 2 are portable and can be used as a desk lamp or attached to a wall or the ceiling. Both kits are quite similar to other (borderline) Tier 1 pico-solar kits available on the market in Rwanda and elsewhere in Africa (see GOGLA 2016). The third kit offered, the *ASE 20W Solar DC Lighting Kit* (“*Kit 3*”), is a SHS, i.e. the solar panel is installed outside and charges a separate battery, which in turn is connected to four LED lamps and a charging station with six USB ports. Kit 3 and its 20 W panel still qualify as Tier 1. It is a small SHS compared to other systems available on the market, but it comes close to Tier 2 in terms of the variety of electricity services. The market prices of the three kits vary considerably, between 13 USD for Kit 1 and 182 USD for Kit 3. According to the solar vendor, the expected lifetime is three years for Kit 1, six years for Kit 2 and four years for Kit 3. Note that the Kit 3 lifetime estimate, in particular, is very conservative. In general, the lifetime of comparable SHS is on the order of 8 to 12 years, but depends on usage patterns and intensity, replacement of components, cleaning of the panel, and environmental conditions (temperature, wind, dust, and humidity).

Table 1. Specifications of Solar Technologies

	Kit 1	Kit 2	Kit 3
			
Model	d.light Design S 2	Greenlight Planet Inc. Sun King Pro 2	ASE 20W Solar DC Lighting Kit
Full battery run time[1] (in hours)	6.5	5.9 - 13.1[2]	4 – 36[3]
Total light output per kit (in lumens)	25	81 – 160[2]	220
Panel size (in Watts)	0.5	3.3	20
Features	1 LED lamp	1 LED lamp, 2 USB ports, 3 brightness settings	4 LED lamps, 6 USB ports, Separate battery of 14Ah
SE4ALL multi-tier classification	Tier 0	Tier 1	Tier 1
Approximate market price in Rwanda	13 USD (10,000 FRW)	37 USD (29,000 FRW)	182 USD (140,000 FRW)
Life span[4]	3 years	6 years	4 years

[1] Run time estimates do not include mobile phone charging; [2] depending on the brightness setting; [3] depending on the number of lamps in use. Sources: https://www.lightingglobal.org, Dassy Enterprise Rwanda; Pictures: Brian Safari, IB&C; [4]According to manufacturer specification.

3.2. Sampling

We used a two-stage sampling approach on the community level and the household level. We selected survey communities so that they resemble typical target regions of solar technologies and used four selection criteria:

(i) Communities are not expected to be connected to the grid in the near future.

(ii) Areas exhibit appropriate solar radiation levels (see Figure 1).

(iii) Communities are not exposed to systematic marketing activities of solar product companies and comparable products are not available in the villages or nearby villages. This reduces the risk of preconceived price ideas, which could lead to strategic bidding in our bidding game. As we will see later, it is impossible to preclude exceptional households from having access to off-grid solar via charities or relatives and friends in urban areas.

(iv) Communities are not adjacent. This prevents communication between survey participants from different communities.

We followed a two-stage sampling process, consisting of non-random community selection, and subsequent random household sampling. First, we obtained a list of communities (so-called *imudugudu*) from the Rwandan government that all met the criteria outlined above, and verified the government's assessment via phone with local authorities at the cell level[3]. Based on these criteria, we compiled a list of eligible communities and then drew 16 out of these, distributed across 11 sectors in three out of five Rwandan provinces (see Figure 1). In a second step, we chose 324 households through simple random sampling on the community level on the day of the field visits. Because not all communities and households were equally accessible, the sample is not equally distributed across communities and sectors (see Figure 1). Households could not self-select into participation.

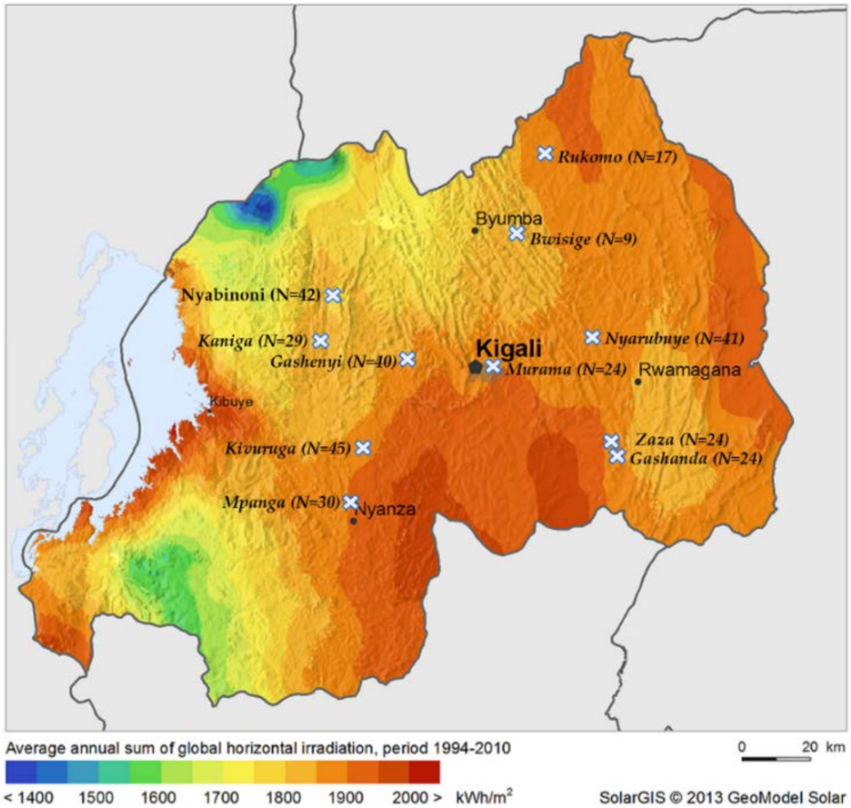
The selection procedure resulted in communities with an average size of 178 households and 847 people. The communities are quite remote, located on average 14 km from the nearest main road, which is a considerable distance for mountainous Rwanda. Public infrastructure is available only in a few communities; this includes primary schools (in five communities), health centers (in one community), and weekly markets (in five communities). Only two of 14 community chiefs interviewed expect their community to be connected to the national electricity grid in the near future.

In line with our selection criteria, communities are not exposed to systematic promotion of solar products. Off-grid solar products comparable to our Kit 1 and Kit 2

[3] Rwanda is divided into five administrative levels, including provinces, districts, sectors, cells, and imudugudu. 416 sectors cover 2,148 cells, of which each covers on average seven imudugudu (see National Institute of Rwanda 2008).

are not available in local shops. Only around half of the communities had some exposure to NGO-led marketing activities of larger SHS. As we show later, the technology is not completely new to the population, but adoption rates of solar products before the study were low (41 households) and prices were unknown (see Section 4.1).

Figure 1. Sectors Surveyed and Global Horizontal Irradiation Levels



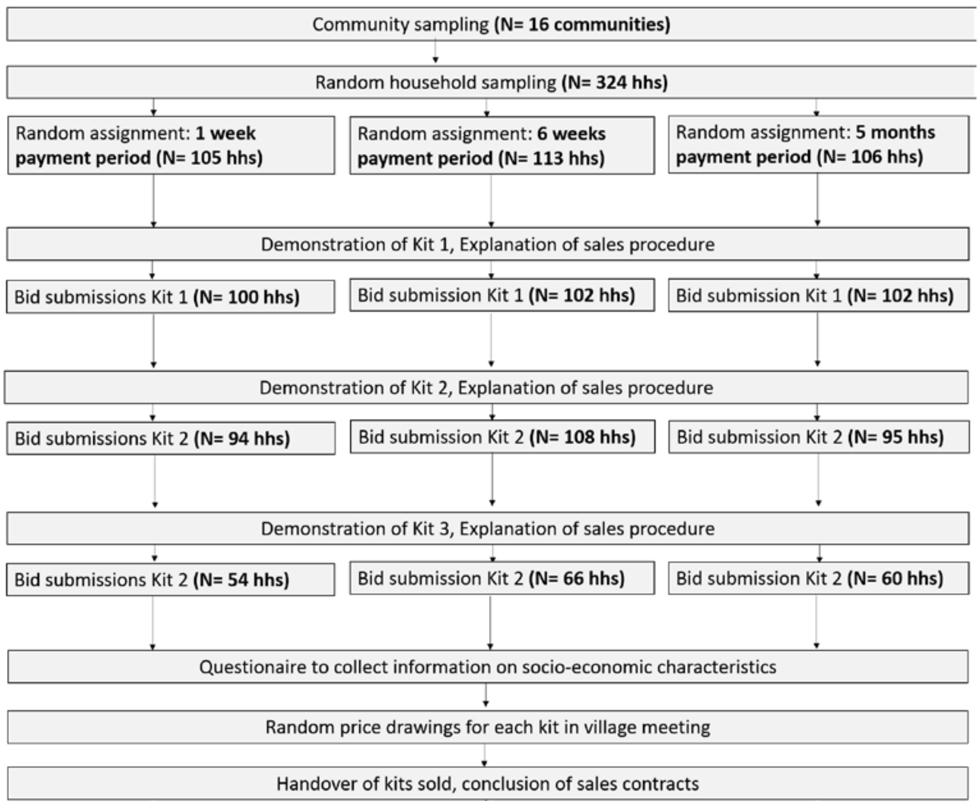
Note: Crosses indicate the sectors surveyed, which contain between one and two surveyed imudugudu. The sample size surveyed per sector is in parentheses. Source: Own illustration based on SolarGIS Solar Radiation Map for Rwanda.

3.3. Survey Implementation and the Real-Purchase Offer Game

The survey was implemented between August and November 2015 in cooperation with *Inclusive Business and Consultancy (IB&C),* a Kigali-based consultancy, *Rwanda Energy Group (REG),* Rwanda's public energy agency, and *Dassy Enterprise,* a Kigali-based Rwandan company that markets branded solar products.

For the household interviews, the financial decision maker was called and informed that we would sell a solar kit following a sales procedure different from what is usually known in the market. All sampled households were asked for their consent to be interviewed and to participate in the bidding game, but were not informed about the research purpose or the experimental character of the study, i.e., the randomization of the payment periods. Hence, typical survey effects might occur, but Hawthorne effects are unlikely. Enumerators worked in parallel within one community to avoid communication between participating households. Figure 2 presents the participant flow, which highlights our sequential procedure in the field.

Figure 2. Participant Flow



The enumerator demonstrated the three solar kits to each household consecutively and offered the opportunity to bid for each one using the auction procedure described below. The process started with Kit 1, followed by Kit 2, and lastly Kit 3. When Kit 1 was offered, the household was not yet aware of the Kit 2 and 3 offers. Before Kit 2 was offered, the participants were told that they can only purchase one kit, and asked to decide which kit they would buy in case they make successful bids for both. Likewise, before Kit 3 was offered, participants were asked to decide which kit they would buy in case of two or three successful bids.[4]

The enumerators followed the same procedure for each kit. First, they demonstrated the kit. The enumerators had been trained beforehand by *Dassy Enterprise* to convey the key product information. Kit 1 and Kit 2 were demonstrated during the interview, while Kit 3 was too heavy to be taken to each household and was therefore only described in all details. Second, enumerators explained the BDM real purchase offer procedure. Respondents were instructed that they could purchase the product only if their bid exceeded or equaled the randomly drawn price. The price to be paid was the randomly drawn price, not the stated one. This price would be drawn in public in the afternoon.[5] Moreover, it was explained that the household would not be allowed to purchase the product if its bid fell below the randomly selected price; in other words, changing the bid afterward was not possible. It was emphasized that the price was not negotiable; it could not be influenced in any manner by the enumerator or the household. Third, the randomly assigned payment period (one week, six weeks or five months) was announced. The interviewed households were then offered the solar kit and asked for the highest price they would be willing and able to pay.

We opted for the BDM approach, because, unlike stated WTP approaches, it incentivizes truthful responses. 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 was less than or equal to her valuation. Another useful feature of BDM is that it allows for observing exact point-of-purchase prices, i.e., it allows for drawing a detailed demand curve. It hence yields more precise, higher-resolution data on households' WTP as compared to take-it-or-leave-it approaches, which provide only WTP bounds.

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[4] This procedure ensures independence between bids. A downward bias due to bid dependence is very unlikely for two reasons. First, households were not aware of the Kit 2 (or 3) offer when bidding for Kit 1 (or 2). Second, the capacity of the kits presented increases consecutively. A potential upward bias may still arise if households increased their bid more than they increased their actual valuation because they reasoned that the superior kit introduced next should have a higher price than the one formerly presented. However, theoretically, incentive compatibility of the BDM approach should prevent this. Note that only five households made inconsistent bids, i.e., higher bids were made for a smaller kit than for a larger one.

[5] Note that this price randomization on the village level does not require correct standard error estimates using bootstrapping or randomization inference, because the price draw is not the treatment as is the case in a standard RCT, i.e., we do not evaluate the effect of the price draw on behavior.

Furthermore, compared to a Vickrey second-price auction, the BDM set-up prevents collusion or conflict between different bidders during the bidding process, because they do not bid against each other, but against a random price draw.[6] However, the BDM method is sometimes criticized for its complexity. In particular, in poor rural settings, the respondents' comprehension can be a bottleneck. Therefore, before we offered the solar kits, we conducted a hypothetical practice round with a mobile phone without a real purchase.

The households were informed that *Dassy Enterprise's* field services would provide a one-year warranty. In this rural Rwandan context, warranties are uncommon, and signal good quality. The instructions the enumerators presented to the participants before the game furthermore contained some soft marketing messages (see Appendix A for the experiment instruction). The key features of the three kits were introduced, including the different electricity services they would allow for. Participating households were informed about average spending of rural Rwandan households on batteries, kerosene, and candles, i.e., those sources that can be replaced by the solar kit, using the information we collected during earlier surveys (see Lenz et al. 2017). We administered our socio-economic questionnaire only *after* the bidding processes for the three kits, in order to avoid distorting effects on the participants' mind set or bidding behavior.

Moreover, the participant was informed about the minimum and maximum prices in the draw. The lower bounds of these ranges were set at a very low price level of approximately 30 percent of the market prices for Kit 1 and Kit 2 and at 65 percent of the Kit 3 market price.[7] The upper price bounds were the Rwandan market prices of the respective solar kit. The price range was disclosed to the participant because, based on preparatory field visits, we expected very low knowledge about actual prices in the rural population and figured that an entirely non-anchored WTP might even discourage participation.[8] We chose this upper bound to be sufficiently high to cover the participants' maximum WTP (which turned out to be true). The participants were simply informed once about the price ranges, without any further appeal to bid within this range (see again Appendix A).

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[6] See Berry et al. (2015) for a profound discussion of BDM.

[7] The price range was between 4 USD and 13 USD for Kit 1, 13 USD and 38 USD for Kit 2, and 115 USD and 182 USD for Kit 3.

[8] Answering a non-anchored WTP question can be cognitively very challenging (Kaas et al. 2006), particularly when participants are confronted with an unknown product.

After the household visits were completed, the random price draw for each solar kit was done openly in an afternoon community meeting in the presence of all participants. We decided to draw prices at the community level (i.e., one price per kit and community) instead of at the household level, in order to avoid social tensions induced by different prices within the same community.

Those participants whose bids exceeded the drawn price received the product the same day and signed a binding sales contract. Beyond the contract, no sanctions in case of non-payment were announced. Participants were offered the possibility to make a voluntary advance payment. Remaining payments could be made in installments via mobile banking through one of the three Rwandan mobile phone operators.[9] At the time of survey implementation, *Dassy Enterprise* and other Rwandan small solar kit providers did not offer payment schemes featuring remote monitoring to shut down the solar kit (see Sections 2.1. and 4.4.). All but two households were sufficiently familiar with mobile banking services. These two households had already opted out of the game during the interview.

4. Results

4.1. Summary Statistics and Balancing Test

Table 2 summarizes the key socio-economic characteristics of our sample and tests whether the randomized payment period groups are balanced. The multiple *t*-tests show that the groups do not differ significantly. For those variables that do exhibit statistically significant differences, the magnitude of the difference is small. We will nonetheless control for all the variables in the subsequent evaluation of the randomized payment schemes.

Around 13 percent of our sample (41 households) already possessed a solar kit. The majority of these households (63 percent) received their kit from urban areas, presumably from friends or relatives. In order to test whether respondents had preconceived price information, after the bidding game we asked them to guess the market prices of the three kits. This variable confirms that most of the solar kit-owning households received them at no cost, as only five out of the 41 households were able to name a price. Among the 88 percent of survey participants that did not yet possess a solar

[9] The payment conditions were explicitly explained before conducting the BDM game.

kit, only 10 respondents said they had an idea of the market price. This suggests that information about solar kit prices is very limited in the surveyed communities.

The WTP expressed by solar-kit-owning households in the bidding game is likely to convey a different message than the one expressed by households without a kit, because they bid for a second modern lighting source. The same might apply to households that already own a rechargeable lamp or a car battery; both are typically charged by the users in shops that have a generator or in the next grid covered communities. We therefore control for these electricity sources in our assessment later in this section.[10]

Table 2. Descriptive Statistics and Balancing Test for Randomized Payment Periods

	Mean full sample	*p*-value Period 1 vs. Period 2	*p*-value Period 1 vs. Period 3	*p*-value Period 2 vs. Period 3
Socio-economic characteristics				
Female respondent/bidder	0.42	0.472	0.829	0.347
Head of HH years of education	4.44	0.439	0.399	0.117
HH size	4.53	0.118	0.640	0.038*
Head of HH is a farmer	0.80	0.780	0.471	0.650
Share of students in HH	0.30	0.013*	0.632	0.037*
House with tile roofing	0.21	0.769	0.220	0.340
Monthly non-energy expenditures (USD) [1]	57.68	0.025*	0.081*	0.821
Baseline energy consumption				
Monthly phone charging expenditures (USD)[1]	1.11	0.634	0.409	0.664
Monthly energy expenditures (USD)[1,2]	8.71	0.059*	0.252	0.348
Owns rechargeable lamp	0.08	0.680	0.486	0.262
Owns car battery	0.02	0.052*	0.083*	0.767
Owns solar kit	0.13	0.238	0.845	0.324
N	324	218	211	219

Note: *** p<0.01, ** p<0.05, * p<0.1 denote statistical significance. [1] The values are bottom and top coded at 2% and 98% of the distribution respectively to eliminate outliers. [2] Including expenditures on kerosene, dry-cell batteries, and candles; we excluded expenditures for charcoal and firewood, since the services for which these fuels are used (cooking, ironing) are not replaceable by solar kits; for those 26 households that own a rechargeable lamp, we did not elicit expenditures for recharging the lamp.

To get a sense of the net savings potential, we now consider the price of each kit in relation to the total energy expenditures that it can replace. This provides us with an

[10] As a robustness check, we redo the WTP analysis for a restricted sample for which we exclude households that already own a solar kit or a car battery. Results can be found in Appendix B, Table B2. It shows that the results in the following sections are robust to the exclusion of these households.

estimate of the amortization period when only immediate monetary savings are taken into account. Because the smaller kits in particular will not replace these costs completely, we use a 'replacement factor' (RF, derived from Grimm et al. 2017) that approximates the share of expenditures on kerosene, dry-cell batteries, and candles to be effectively replaced by the solar kits. We assume that Kit 1 and 2 will replace approximately 75 percent of lighting expenditures (see Table 3). Kit 2 further replaces 75 percent of radio and all phone charging expenditures. Kit 3 replaces all traditional energy sources in these categories. Based on these assumptions, Table 3 shows that the amortization periods for the three kits are on average 14, 17, and 68 months. Note that, according to the expected lifetime that Dassy communicates to customers, Kit 3, unlike Kit 1 and Kit 2, would on average amortize only after the end of its lifespan (see Section 3.1).

Table 3. Savings Potential of Solar Kits

Kit	Average replaceable energy expenditures in USD on…* RF					Total monthly savings (in USD)	Amortization (in months)
	…phone charging	*…candles*	*…batteries for lighting*	*…kerosene for lighting*	*…batteries for radio*		
1	1.11 * 0.00	0.16 * 0.75	0.66 * 0.75	0.43* 0.75	0.28 * 0.00	0.94	14
2	1.11 * 1.00	0.16 * 0.75	0.66 * 0.75	0.43 * 0.75	0.28 * 0.75	2.32	17
3	1.11 * 1.00	0.16 * 1.00	0.66 * 1.00	0.43 * 1.00	0.28 * 1.00	2.64	68

Sources: Expenditures data from own data set. RF abbreviates replacement factor.

4.2. Revealed Willingness to Pay in Bidding Game

Virtually all visited households agreed to participate in at least one of the three bidding games (see Table 4). In total, 164 households won the bidding game, i.e., at least one bid exceeded the randomly drawn price (66 households for Kit 1, 88 for Kit 2 and 10 for Kit 3). Only ten of these 164 winning households refused the purchase, either because they noticed afterward that they bid too high (four households) or, after the price drawing, they wanted a different kit than the one for which they successfully bid (six households).[11] Effectively, 154 households purchased a kit.[12] As can be seen in Table 4, some households did not make a bid. The highest share of non-bidding is observed for Kit 3 (44 percent), whereas it is clearly below 10 percent for Kit 1 and 2. The dominating reason for non-bidding is that households were not willing or able to make a bid above the lower bound (remember that the range for the randomly determined prices was disclosed before the game).[13] In order to avoid a potential bias because of this opting-out behavior, we estimate a Tobit model to account for the censored sample.

The results of the bidding game can be found in Table 4, not yet accounting for the different payment schemes. We show both the WTP of those households that made a bid and the corrected WTP using the Tobit model. The average bid for Kit 1 across all treatment groups was roughly 5 USD, which is equivalent to 38 percent of the market price. The price bid for Kit 2 was slightly less than 17 USD, covering 45 percent of the market price. For Kit 3, the average bid was 97 USD, which covers 54 percent of the market price.[14, 15]

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[11] We asked respondents for their satisfaction with their bid after the community price drawing. The vast majority were satisfied with the bids. Only one bidder was unsatisfied because s/he bid too much and 12 percent of bidders were unsatisfied because they bid too little. This latter reasoning implies either that these bidders bid below their valuation or that their valuation changed between bid and the price draw, for example, due to envy or social comparison.

[12] In total, 51 participants won two auctions. 43 bidders won the two smaller kits; of these bidders, the majority (39) had chosen beforehand to take Kit 2. Three participants won Kits 1 and 3; of these bidders, two picked Kit 1. Five participants won Kits 2 and 3, and four of them purchased Kit 3. In addition, eight participants won bids for all three kits. Most (5) had decided beforehand to buy Kit 2, whereas two participants chose Kit 1 and one participant chose Kit 3.

[13] More specifically, for Kit 1, all 13 participants who opted out claimed that the kit would not fulfill their needs, almost entirely because it does not charge phones. Similarly, half of the 26 respondents who opted out from bidding for Kit 2 claimed it would not fulfill their needs, while 35 percent cited a lack of financial resources, 12 percent already owned a kit, and two households did not want to use mobile money. For Kit 3, 82 percent did not have the financial resources to bid and15 percent did not like it. One household said the payment period was too short.

[14] The WTP for the restricted sample, excluding those households that already possessed a solar kit or a car battery before our visit, shows that our results are robust. The WTP values are quite similar at 4.91 USD for Kit 1, 17.24 USD for Kit 2, and 94.51 USD for Kit 3.

[15] The corresponding WTP in the Lee et al. (2016) study is around 147 USD. Unlike our BDM approach, those authors used a take-it-or-leave it approach to elicit WTP, and observed adoption rates for four different price points on the demand curve. While the authors did not analyze the average WTP across the sample, the value corresponding to our average WTP can be obtained by dividing the fitted consumer surplus of 12,421 USD by the average community population of 84.7 households.

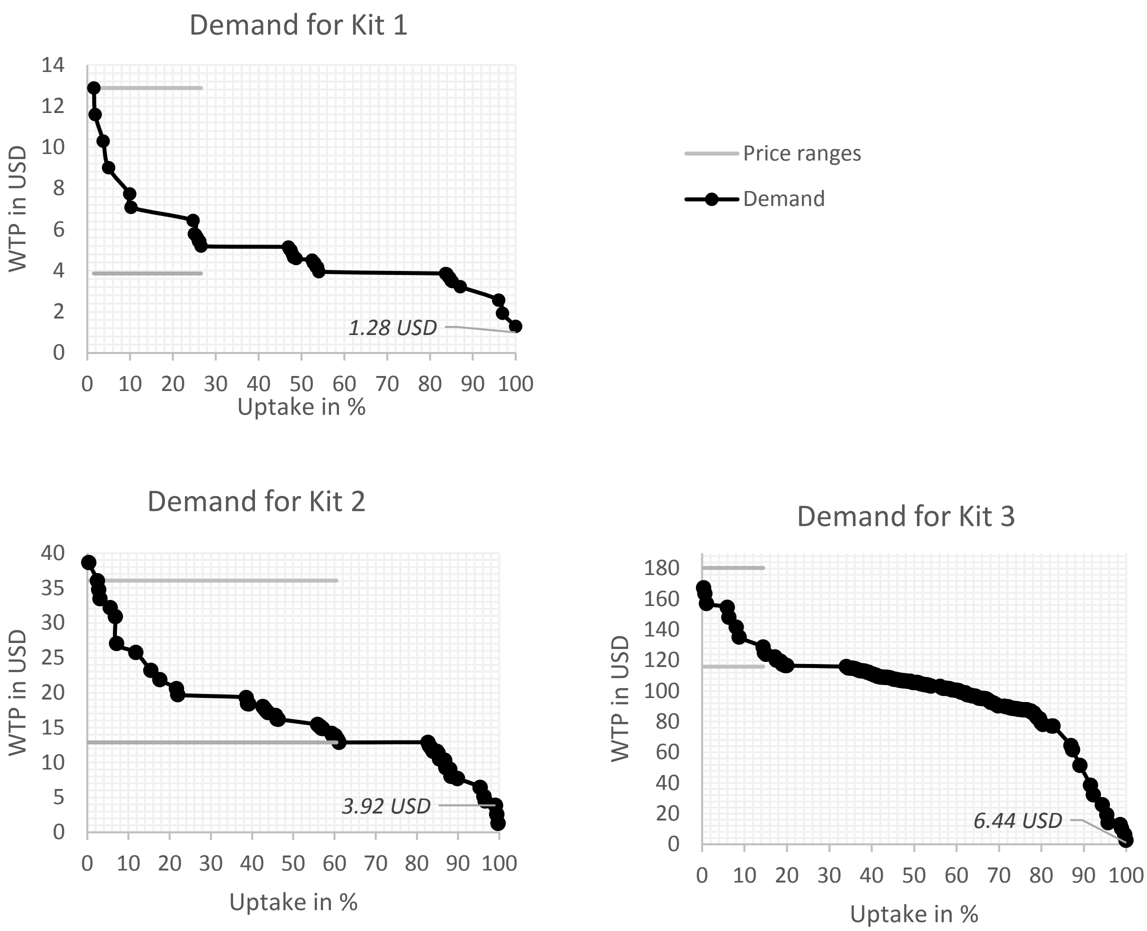
Table 4. Bidding Game Outcomes

	Kit 1	Kit 2	Kit 3
Respondent participates in bidding game	0.94	0.92	0.56
Market price (USD)	13	36	182
Bid amount, bidders only (USD)	4.92	16.84	93.84
	(2.06)	*(7.16)*	*(45.17)*
Bid amount full sample (USD, Tobit corrected)[1]	4.90	16.66	96.88
	(2.01)	*(6.95)*	*(34.60)*
Bid as share of total monthly expenditures[1,2]	18.86	58.36	294.84
	(20.46)	*(57.82)*	*(328.54)*
N Sales in experiment	66	88	10
N contracts effectively signed	60	84	10
Number of observations	324	324	324

Note: Standard deviations in parentheses. [1] Values are bottom and top coded at 2% and 98% of the distribution respectively to eliminate the effect of outliers. [2] Excluding expenditures on wood and rechargeable lamps.

Figure 3 uses the households' WTP to illustrate the demand curves for the three kits. The figure shows that the end-user prices at which full uptake would take place in our sample amount to less than 10 percent of the kits' market prices, namely 1.3 USD for Kit 1, 3.9 USD for Kit 2, and 6.4 USD for Kit 3.

Figure 3. Demand for Solar Kits



Note: Price in italics refers to price that would lead to 100 percent uptake. The demand curves are based on bids by households. For households that opted out of the bidding, we estimate values via a Tobit estimation (see Section 4.3).

The distribution of bids displayed in Figure 3 suggests an anchoring effect due to the announcement of price ranges, in that the observable bids cumulate above the lower price bound for Kits 1 and 2. Two distortive effects can lead to this bidding behavior. First, as mentioned above, bids could be biased downwards if participants – in spite of the incentive-compatible BDM mechanism - gamble to get the kit at the lowest price. Second, bids could be biased upwards if participants with a real WTP slightly below the lower bound are tempted to adapt it to this lower bound. Even if we – conservatively – assume the estimates to be slightly biased downwards, it seems safe to conclude that, for the vast majority of households, the true willingness to pay is clearly below the market price. Only very few observations reach this upper bound.

Comparing the bids to the households' total expenditures reveals the priority that modern lighting constitutes for people in rural areas (see Table 4). While the WTP for Kit 1 already corresponds to almost 20 percent of people's monthly expenditures, the increase of bids when phone charging services are added is especially striking. For Kit 2, the average WTP corresponds to 58 percent of the total monthly expenditures. For Kit 3 the average bid corresponds to 295 percent of the bidders' monthly expenditures.

4.3. Effect of Liquidity Constraints

In this section, we examine the causal effect of relaxing liquidity constraints on the bidder's WTP. We regress the bidders' WTP values for each of the three solar kits in a log-linear model on the randomized payment scheme and a set of socio-economic control variables. We again account for the censored samples by using a Tobit Model. For all three kits, we include community fixed effects and control for the date of the bidding game. The date might have an effect because the survey work was spread across three months and the later interviews were closer to Rwanda's second harvest period in December. Standard errors are clustered at the community level. The results are shown in Table 5. We subsequently include the two sets of control variables already presented in Table 2, i.e., socio-economic characteristics and baseline energy consumption variables. The latter might be endogenous to the reported WTP, but they could as well be important covariates leading to an omitted variable bias if not accounted for. As we will see, the results turn out to be robust, so both potential biases are probably negligible.

The effects of relaxing liquidity constraints are very consistent across the three kits. Offering a six-week payment period instead of a seven-day payment period increases the WTP, but the increase is small in size and not statistically significant. For all three kits, the five-month treatment increases the WTP by 7 to 12 percent and the increases are at least borderline statistically significant. Yet, the positive treatment effect vanishes when discounting the WTP for a 2.5 percent monthly interest rate applied to each of the two treatments (not shown in the table; see Section 5.1. for a discussion).

Table 5. Payment Periods and Willingness to Pay

	Kit 1			Kit 2			Kit 3		
Payment periods									
Payment period: 6 weeks	0.013	0.014	0.021	0.059	0.061	0.062	0.067	0.060	0.065
	(0.778)	(0.774)	(0.633)	(0.372)	(0.340)	(0.311)	(0.193)	(0.240)	(0.203)
Payment period: 5 months	0.112	0.118	0.106	0.100	0.102	0.081	0.073	0.085	0.067
	(0.035)**	(0.012)**	(0.037)**	(0.130)	(0.108)	(0.146)	(0.149)	(0.089)*	(0.184)
Pseudo R-squared	0.126	0.179	0.159	0.144	0.204	0.236	0.186	0.266	0.206
Observations	324	323	324	324	323	324	324	323	324
Prob > chi2	0.035	0.010	0.073	0.319	0.271	0.351	0.281	0.210	0.300
Control variables included									
Community and time	YES	YES	YES	YES	YES	YES	YES	YES	YES
Socio-economic characteristics	NO	NO	YES	NO	NO	YES	NO	NO	YES
Baseline lighting consumption	NO	YES	YES	NO	YES	YES	NO	YES	YES

Note: p-values are displayed in parentheses, where *** p<0.01, ** p<0.05, * p<0.1 denote statistical significance. The dependent variable is log(WTP). We display marginal effects from a Tobit estimation. The base category is a one week payment period. Table B.1 in the Appendix B shows the complete regression results including control variables.

4.4. Default Rates

This section explores the challenges in collecting instalment payments. These challenges are typical for many rural African markets and thereby constitute substantial transaction costs in disseminating market-based off-grid solar power to the rural poor. We used a PAYG model similar to that of many other providers, in which participants agreed to a contract to pay small instalments over time via mobile money.

Only 17 percent of participants paid the full price on their own initiative and within their payment period. Participants were not reminded before this period expired. The share of full payments is highest, at 37 percent, in the one-week payment group compared to the six weeks (11 percent) and five months groups (9 percent). Figure C in the Appendix C graphically shows the payment behavior over time. Our field team started calling overdue participants only after the respective payment period had expired. The purchasers were reminded up to nine times over a period of six months. In total, 488 reminder calls were made. The most typical response to these calls was a payment promise (over 50 percent), followed by referring to financial bottlenecks, sickness, and dissatisfaction with mobile money (about 10 percent each). It was never stated that non-payment was due to quality issues or dissatisfaction with the kits. For participants in default, our field team eventually contacted community authorities and revisited the defaulting participants to announce that the kit would have to be returned in case of further payment delays. This encashment process increased the rate of fully paid kits considerably, from 17 to 65 percent by September 2016, i.e., around 14 months after the experiment, which is a fairly high payment share and in line with comparable exercises (see Tarozzi et al. 2014).[16]

It is true that novel PAYG features, for example, those that turn off the kit remotely in case of non-payment, are likely to improve the repayment behavior. Yet, we would argue that a major reason for the challenges that we experienced are affordability issues among the poor rural target group. While the specific numbers presented above are of course not transferable to other settings, the observation of a very challenging repayment processes probably is generalizable – at least if we postulate that the market reaches out to poorer strata, which is necessary to achieve the universal access goal.

5. Interpretation of Results

In this section, we interpret our findings in light of two perspectives. First, in the *SE4All angle*, we discuss the implications of our results for the market-based approach currently favored by the SE4All initiative and pursued by many governmental interventions. Second, in the *Social Planner's angle*, we provide a back-of-the-envelope cost-benefit analysis of a full subsidization policy.

5.1. Sustainable Energy for All Angle

Households in our remote rural areas are on average willing to pay prices that cover only half of the current market prices, at most. It will hence be difficult to reach the very poor, and thus achieve universal access, with a solely market-driven approach. Yet, this low WTP clearly does not reflect a lack of interest, as signaled by an average WTP of 295 percent of total monthly expenditures for Kit 3. This number indicates a high valuation of off-grid solar electricity relative to household income. Qualitative statements in open interviews also confirmed the importance of electricity for households, even if provided by off-grid solar rather than by grid connection.

The effect of extended payment periods on WTP is between 7 and 12 percent for the five-month payment period. This increase has to be put in perspectives with interest

[16] Compared to default rates in the micro-finance sector, ours are quite high. This comparison, however, is not too relevant to our case. A pivotal difference is that we approached a random sample of all households, whereas micro-finance loans are taken up by a self-selected and probably more solvent sample of households.

rates on local formal and informal capital markets. Savings and Credit Cooperative Organizations (SACCOs), the most accessible formal source of financing, offer credit in rural Rwanda at interest rates of 2.5 to 5 percent monthly (AFR, AMIR and MicroFinanza Rating 2015), which roughly corresponds to the increase in WTP. Hence, when we apply this interest rate to our zero-interest rate payment periods, the positive treatment effect on the WTP vanishes.

It is worth noting that these high interest rates are also related to the low repayment rates that we observed. While the repayment rates described in Section 4.4 are specific to this scenario, we believe that our experience is an indicator of generally high transaction costs and default rates in rural areas. In a market-based approach, these transaction costs have to be borne by the companies and might easily become prohibitive.

It might be that the payment schemes we offered are not long enough, especially for Kit 3. Poor households might be particularly interested in payment schemes that enable them to make the investment without changing their cash flow over time, which would require that the investment amortizes within the payment period. To assess this, the stylized calculations we performed in Table 3 are helpful. A payment period that enables households to invest in off-grid solar without changing their cash flow over time would have to be as long as the amortization periods of 14 months, 17 months, and 68 months for Kit 1, 2, and 3, respectively. While the payment periods for Kit 1 and 2 could be realistic in real-world loans, a 68-month period probably is not. For the *SE4ALL* perspective, it is important to note that this amortization period is very heterogeneous across the expenditure distribution. This is because replaceable energy expenditures (mostly on kerosene and dry-cell batteries) vary considerably. For the highest expenditure quintile, the amortization period decreases to 9, 13, and 48 months. This reduction is considerable and hints at the success stories of M-Kopa and d.light, which target the non-poor rural strata. For the poorest quintile, by contrast, the investment into the three devices pays off only after 18, 26 and 106 months, which indicates that payment periods have to be extended dramatically to allow the poor to invest without changing their expenditures over time.

In sum, these considerations show that a purely market-driven approach is unlikely to reach broader sections of the population. The poor’s ability to pay is low and their amortization periods are particularly long. Moreover, as discussed in Section 4.4, transaction costs are high in such markets, which is also reflected in high interest rates in capital markets.

5.2. Social Planner's Angle: A Stylized Cost-Benefit Analysis

In this section, we assess the social cost-effectiveness of a full subsidization policy that reduces the end-user price to zero. We contrast the cost of this policy – approximated by the solar kits' market prices - with its internalized benefits – approximated by the WTP. Since this WTP probably accounts only for internalized benefits, but not for external effects or long-term private benefits, we label the gap between cost and WTP the *internal return on investment gap.*[17] For on-grid electrification in Kenya, Lee et al. (2016) estimate this gap to be between 511 USD and 1,100 USD per household.[18]

In order to approximate the cost of a full subsidization program, we use the prices charged by Rwandan last-mile distributors. It is plausible to assume that these prices cover all logistics and servicing network costs. We thereby abstract from additional administrative costs, but also from potential economies of scale.

Table 6 shows the cost and benefits of our solar off-grid devices, as well as the resulting *internal return on investment gap.* In line with our observation in Section 4.2, it shows that the *gap* amounts to 8 USD per household for Kit 1, 21 USD for Kit 2, and 85 USD for Kit 3. Hence, the average cost clearly exceeds average internalized benefits. However, this *gap* per household is much smaller than for on-grid electrification.

Table 6. Cost and Direct Benefits of Off-grid Electricity Per Household

	Kit 1	Kit 2	Kit 3
Cost in USD	12.90	37.40	182.00
Direct Benefits in USD (as reflected in WTP)	4.90	16.70	96.90
Internal return on investment gap in USD	8.00	20.70	85.10

Note: Tobit corrected WTP values are used; see Table 4.

So far, this calculation ignores replacement investments that are required after the lifespan of the solar kits. Yet, even when accounting for replacement investments, our overall conclusion should hold. To illustrate this, a very conservative lifetime estimate of Kit 1 is at least three years, Kit 2 six years, and Kit 3 four years. Even if we assume

[17] Lee et al. (2016) use the terms 'welfare loss' and 'social costs'.

[18] Note that the household grid connection costs in Kenya are not extraordinarily high. For rural Rwanda, Lenz et al. (2017) report that grid connection cost in the extensive grid roll-out program EARP amounts to around 1,500 USD per household. Chaplin et al. (2017) observe a connection cost in Tanzania of 6,600 USD per household. See as well World Bank (2009) for an overview on grid connection cost in Africa.

replacing the solar kits after their respective lifetimes (i.e., a number of replacements over a 20-year period), the *internal return on investment gap* accumulates to 53 USD for Kit 1, 69 USD for Kit 2, and 426 USD for Kit 3 and thus is still less than for on-grid electrification. Note that this is very likely a conservative assessment, as production costs of off-grid solar are constantly decreasing.

Should the social planner hence invest in a full subsidy for the distribution of off-grid solar? Leaving the normative SE4All goal aside, this would be the case as soon as the external effects and non-internalized private benefits are high enough to close the *internal return on investment gap*. Theoretically, there are three types of effects that are not covered in our WTP values. First, households do not account for external effects. These could be, for example, reductions in environmental damages from kerosene and battery use or positive spillovers to neighbors who seize the lighting, radio, or phone charging opportunity. There is no evidence on spillovers, but, as for environmental effects, quality-verified off-grid solar in particular can decrease e-waste in countries with poor waste management infrastructure (see Grimm et al. 2017; Grimm and Peters 2016; and Bensch et al. 2017).[19] The impact on greenhouse gas emissions, in contrast, is probably small (see Baurzhan and Jenkins 2016).

Second, households' WTP might not reflect private benefits from solar kit usage that are unknown, uncertain, or that materialize only in the very long run. These include improved security, cleaner air and the related reduction in health hazards, as well as the improved studying and working conditions and their potential positive effects on future employment. Grimm et al. (2017) in Rwanda, Rom et al. (2016) in Kenya, and Samad et al. (2013) in India provide evidence for effects on productivity of housework activities, health, and study time of children, which, however, does not necessarily imply immediate increases of educational or economic development outcomes. Grimm et al. (2017) furthermore observe that off-grid solar considerably reduces the consumption of dry-cell batteries, which are increasingly used for lighting purposes at the baseline and largely disposed of inappropriately outdoors. Aevarsdottir et al. (2017) find exceptionally pronounced impacts of off-grid solar in Tanzania. They not only observe effects on direct outcomes such as expenditures and phone charging, but also on labor supply and income. Focusing on educational outcomes and health, Kudo et al. (2017a and 2017b) as well as

[19] Calculating the comprehensive environmental balance for off-grid solar is non-trivial, since it heavily depends on the environmental cost of solar kit production as well as the battery content and disposal systems at production and consumption sites.

Furukawa (2014) also observe that off-grid solar is indeed used for studying purposes. Yet, in their trials in Bangladesh and Uganda, this does not translate into effects on ultimate school performance indicators or respiratory symptoms.

Third, households might face liquidity constraints beyond those that are removed by our payment periods. There is not much evidence in the literature on the specific role of credit schemes. Collings and Munyehirwe (2016) evaluate a PAYG scheme in Rwanda and observe that mostly wealthy households make use of the financing scheme. Yoon et al. (2016) confirm our findings and observe only a very subtle effect of an extended payment period on the WTP.

Hence, overall, while impact findings are heterogeneous, the literature tends to agree that off-grid solar improves living conditions and thus welfare, but transformative effects on socio-economic development are less likely. It is therefore difficult to provide an unequivocal conclusion on the desirability of subsidies for off-grid solar. However, combining the *SE4All angle* and the *Social Planner's angle* suggests that – if the normative SE4All universal access goal is to be achieved by 2030 – off-grid solar seems to be more promising, since a larger part of the *internal return on investment gap* is covered by non-internalized benefits.

6. Conclusion

This paper has examined the revealed willingness to pay (WTP) of poor off-grid households in rural Rwanda for three different solar lighting technologies. We find that the WTP values are clearly below the market prices of the three offered kits. We have also analyzed the causal effect of randomized payment periods on the WTP and do not observe a positive effect as soon as typical rural interest rates are accounted for.

It is very possible, though, that smarter and longer payment schemes work better to facilitate household investment in off-grid solar. For example, remote monitoring systems can bring down transaction costs considerably. Some off-grid solar companies, such as M-Kopa and d.light in Kenya, have already achieved successes in better-off market segments. However, our evidence suggests that even those modifications and innovations will not solve the affordability problem for the poorer strata, which is also confirmed by Collings and Munyehirwe (2016). Moreover, our WTP analysis for solar kits took a rather static perspective. As solar kits diffuse into the communities, peer effects and social learning are likely to affect WTP values.

The lesson that can be taken away from interpreting our findings within the *SE4All angle* is that a purely market-based approach is unlikely to reach the broader population in these areas. The vast majority are not able to pay cost-covering prices and relaxing credit constraints does not seem to be a panacea. The ambition of the United Nations' initiative Sustainable Energy for All (SE4All) to disseminate off-grid solar to the rural poor via unsubsidized markets might be overly optimistic.

We acknowledge the limits of external validity associated with an experiment in one country, especially in light of the huge Rwandan electricity grid extension program, EARP. This program might affect grid electrification expectations, and hence reduce the WTP. Accordingly, the WTP could well be higher in countries with a less vibrant energy policy. Our affordability result, though, is also informed by our previous work on energy access in other countries (see Bensch et al. 2016 for a study on Burkina Faso, as well as Grimm and Peters 2016, and Peters and Sievert 2016 for a review of several countries). This synthesis will be transferable to many other regions in rural Africa, in particular to the large number of countries that are so far not on the radar of the off-grid solar business.

Now, turning to the *Social Planner's angle*, we have shown that the *internal return on investment gap*, i.e., the difference between the cost of electricity provision and the internalized benefits, is lower for solar off-grid electrification than for on-grid electrification. This is mainly due to the high investment costs of grid electrification. In terms of non-internalized benefits, the literature provides some evidence that off-grid solar does not create a massive socio-economic transformation, but positive pro-poor impacts are likely and noteworthy given the low investment cost. Although off-grid solar does not allow for any substantial commercial usage, it seems likely that external and non-internalized private benefits close larger parts of the *internal return on investment gap* than benefits of on-grid electrification do. Earlier research has also shown that electricity consumption levels even in grid-connected areas in Africa are very modest (see Chaplin et al. 2017; Lenz et al. 2017; and Peters et al. 2011). Such low consumption levels can well be met by off-grid solar. It is furthermore worth mentioning that the WTP values we measure are low in absolute terms but they are quite considerable in relation to households' budgets, indicating that they give off-grid electricity priority over many other important goods. Hence, from a welfare planner's perspective, this makes a case for a policy intervention to facilitate adoption.

Bringing together the two angles, our findings suggest that a subsidization policy is necessary to reach the short-term normative SE4All universal access goal and seems justifiable from a social planner's perspective. For policy, a reasonable way forward could therefore be to facilitate access to off-grid solar technologies for rural households in Africa, not only via indirect promotion policies like tax cuts and supply side interventions, but also through direct subsidies to decrease end-user prices. Such a subsidy scheme should encompass sustainable funding, pro-poor targeting, and a clearly communicated phasing-out strategy. Moreover, off-grid solar does not replace the necessity to build infrastructure. However, instead of rolling out the grid to every rural village in Africa, on-grid investments could be concentrated in certain thriving rural regions with high business potential or in industrial zones to which firms might relocate. Such an integrated on-grid, off-grid strategy would enable industrial development and at the same time achieve broad access to electricity at relatively low cost.

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Appendix A. Experiment Instruction

I now invite you to buy the kit which I just presented to you. The sale is different from usual sales, as the price is not yet fixed. The sale works as follows. You will make a bid for the kit, which means you tell me the exact price you are willing to pay for it. It is good for you to indicate the maximum price you are willing to pay. When you make your bid, remember that you spend a certain amount of money every month on energy to light your house, for example on batteries, candles or kerosene. For all these energy sources, people in rural Rwanda spent on average 2,600 RWF per month. You could hence save this money if you buy the kit. After you made your bid, I will draw a price from this envelope during a village meeting this afternoon *[show envelope]*. There are different prices written on pieces of paper in this envelope. The smallest price is 3,000 RWF (10,000 RWF, 90,000 RWF) and the highest is 10,000 RWF (30,000 RWF, 140,000).

If the price you offer now is lower than the price I draw, you cannot buy the kit. If the price you offer now is higher than the price I draw, you can buy the kit for the price I draw. You only have the option to bid once and you cannot change your bid afterwards. Hence, if your bid is lower than the price I draw, you cannot buy the kit.

After the price drawing in the village meeting, you will have to sign a purchase contract if you won the price drawing. If you cannot pay immediately, you have 7 days (6 weeks, 5 months) to pay for the kit in installments via mobile money. If you want to, you can make an advance payment today. Hence, please make a bid which you are able to pay within 7 days (6 weeks, 5 months).

We will not inform the others about the price you offer to pay. In addition, the result of the price drawing will remain confidential.

I will now give you an example, such that you can better understand the sale process. Imagine I offered you a mobile phone with the same rules. You could for example say that you are ready to pay 3,000 RWF for this phone. Then we draw a price from an envelope.

- The price we draw from the envelope could for example be 2,000 RWF. What would happen in this case? *[Wait for the answer. The correct answer is: I would buy the phone for 2,000 RWF]*

- What would happen if you offer 3,000 RWF and the price we draw from the envelope is 3,500 RWF? *[Wait for the answer. The correct answer is: I cannot buy the phone. Explain again in your own words if necessary, ask for questions, and give another hypothetical example with an imaginary product (not a solar kit) if necessary.]*

Remember that you can cannot change the price you offer after the price drawing from the envelope. This means, you can only make one bid. Also, remember that you have to pay the price in 7 days (6 weeks, 5 months). In addition, be aware that you cannot buy the kit, even if your offer is only a little bit less than the price I draw. *[Verify whether there are still questions. Ask for the bid and assure yourself that the participant is convinced of it]*.

Appendix B. Regression Results

Table B.1. Detailed Regression Results of Table 5

	Kit1			Kit 2			Kit 3		
Payment periods									
Payment period: 6 weeks	0.013	0.014	0.021	0.059	0.061	0.062	0.067	0.060	0.065
	(0.778)	(0.774)	(0.633)	(0.372)	(0.340)	(0.311)	(0.193)	(0.240)	(0.203)
Payment period: 5 months	0.112	0.118	0.106	0.100	0.102	0.081	0.073	0.085	0.067
	(0.035)**	(0.012)**	(0.037)**	(0.130)	(0.108)	(0.146)	(0.149)	(0.089)*	(0.184)
Socio-economic characteristics									
Female respondent		-0.028			-0.084			-0.054	
		(0.517)			(0.031)**			(0.060)*	
Hoh years of education		0.015			0.015			0.007	
		(0.029)**			(0.002)***			(0.122)	
HH size		-0.022			-0.016			-0.002	
		(0.082)*			(0.287)			(0.843)	
Hoh is a farmer		0.059			-0.036			0.034	
		(0.130)			(0.346)			(0.478)	
Share of students in HH		0.001			-0.000			0.001	
		(0.311)			(0.958)			(0.045)**	
House with tile roofing		0.209			0.078			0.052	
		(0.117)			(0.417)			(0.469)	
Monthly non-energy expenditures (USD) [1,2]		0.000			0.001			-0.000	
		(0.737)			(0.126)			(0.696)	
Baseline energy consumption									
Monthly phone charging expenditures (USD)[1]			0.016			0.071			0.013
			(0.341)			(0.000)***			(0.151)
Monthly energy expenditures (USD)[1,3]			-0.001			0.000			-0.000
			(0.141)			(0.726)			(0.922)
Ownership of rechargeable lamp			0.132			0.062			0.048
			(0.028)**			(0.353)			(0.218)
Pseudo R-squared	0.126	0.179	0.159	0.144	0.204	0.236	0.186	0.266	0.206
Observations	324	323	324	324	323	324	324	323	324

Note: p-values are displayed in parentheses, where *** p<0.01, ** p<0.05, * p<0.1 denote statistical significance. The dependent variable is log(WTP). We display marginal effects from a Tobit estimation. We control for community and time fixed effects. Dummy variables taking the value 1 are indicated by "= 1". [1] The values are bottom and top coded at 2% and 98% of the distribution respectively to eliminate the effect of outliers. [2] Excluding energy and phone charging expenditures. [3] Including expenditures on kerosene, gas, batteries, candles and charcoal; excluding expenditures on wood and rechargeable lamp charging.

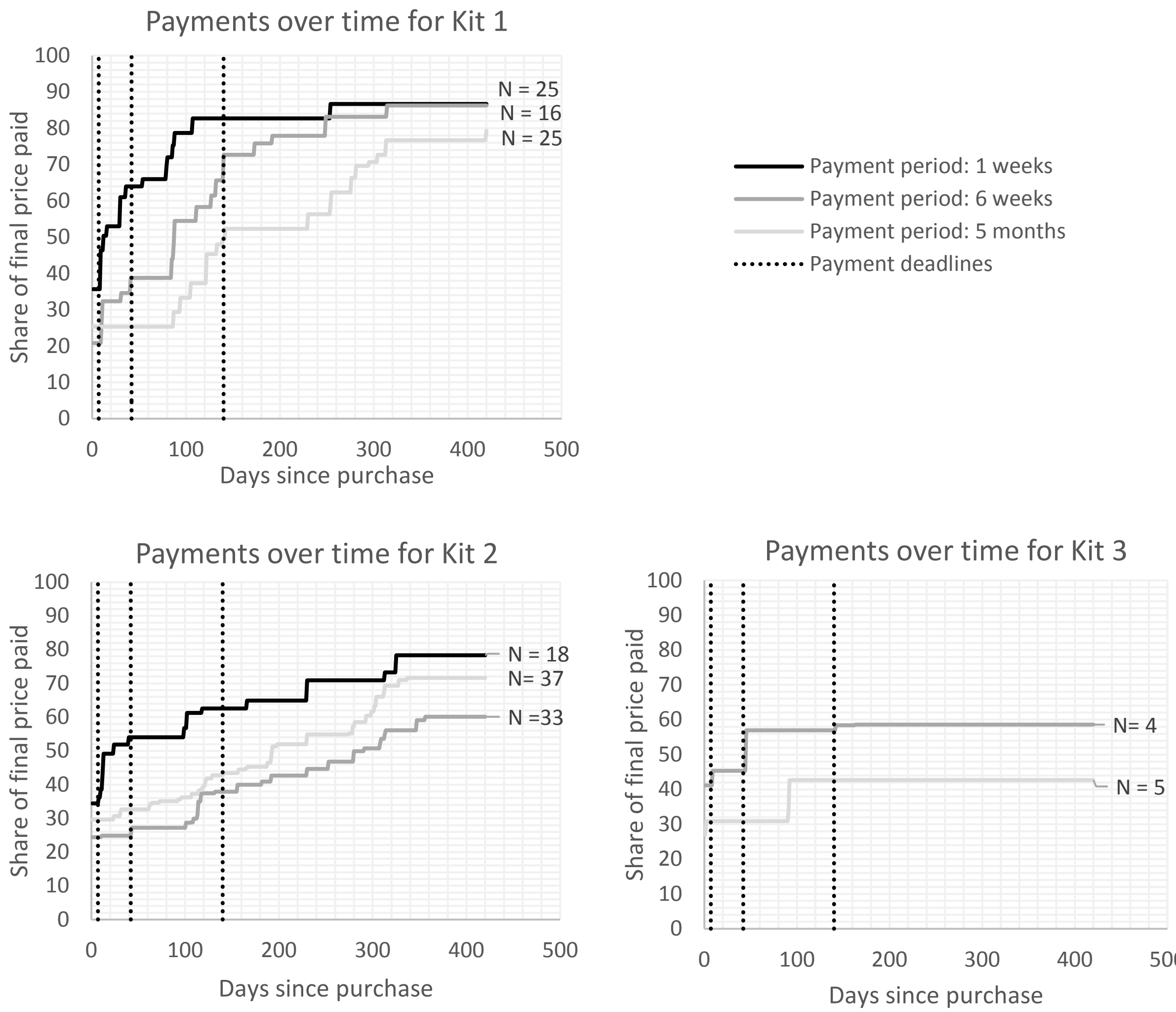
Table B.2. Detailed Regression Results of Table 5 for Restricted Sample

	Kit1			Kit 2			Kit 3		
Payment periods									
Payment period: 6 weeks	0.022	0.019	0.019	0.054	0.060	0.048	0.069	0.069	0.064
	(0.679)	(0.720)	(0.722)	(0.469)	(0.420)	(0.478)	(0.169)	(0.162)	(0.204)
Payment period: 5 months	0.110	0.111	0.108	0.111	0.108	0.093	0.081	0.090	0.072
	(0.067)*	(0.026)**	(0.058)*	(0.120)	(0.129)	(0.127)	(0.087)*	(0.050)**	(0.115)
Socio-economic characteristics									
Female respondent		-0.055			-0.105			-0.041	
		(0.236)			(0.021)**			(0.174)	
Hoh years of education		0.015			0.018			0.007	
		(0.014)**			(0.001)***			(0.055)*	
HH size		-0.033			-0.022			0.005	
		(0.011)**			(0.141)			(0.593)	
Hoh is a farmer		0.059			-0.061			0.074	
		(0.136)			(0.143)			(0.138)	
Share of students in HH		0.002			0.000			0.000	
		(0.126)			(0.742)			(0.476)	
House with tile roofing		0.211			0.069			0.057	
		(0.075)*			(0.504)			(0.469)	
Monthly non-energy expenditures (USD) [1,2]		0.000			0.000			-0.000	
		(0.758)			(0.323)			(0.877)	
Baseline energy consumption									
Monthly phone charging expenditures (USD)[1]			0.007			0.063			0.016
			(0.650)			(0.000)***			(0.104)
Monthly energy expenditures (USD)[1,3]			-0.001			0.000			0.000
			(0.203)			(0.340)			(0.625)
Ownership of rechargeable lamp			0.122			0.122			0.059
			(0.068)*			(0.210)			(0.180)
Pseudo R-squared	0.146	0.215	0.179	0.157	0.233	0.22	0.198	0.283	0.231
Observations	283	283	283	283	283	283	283	283	283

Note: p-values are displayed in parentheses, where *** p<0.01, ** p<0.05, * p<0.1 denote statistical significance. The sample is restricted to households that do not own a modern electricity source, i.e., a car battery or a solar kit. The dependent variable is log(WTP). We display marginal effects from a Tobit estimation. We control for community and time fixed effects. Dummy variables taking the value 1 are indicated by "= 1". [1] The values are bottom and top coded at 2% and 98% of the distribution respectively to eliminate the effect of outliers. [2] Excluding energy and phone charging expenditures. [3] Including expenditures on kerosene, gas, batteries, candles and charcoal; excluding expenditures on wood and rechargeable lamp charging.

Appendix C. Payment Behavior over Time

Figure C. Payment Receipts over Time



Note: N denotes number of sales.