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Willingness to Pay for Electricity Access in Extreme Poverty

Evidence from Sub-Saharan Africa

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Abstract

Improving electricity access in low-income countries is a challenging problem because of the high costs of grid extension and low demand for grid electricity in rural areas. This study elucidates these constraints by analyzing poor households' willingness-to-pay for different types of electricity access, including lower cost off-grid technologies. The theoretical model illustrates how consumer preferences, operational and capital costs of electricity service delivery, and availability of power supply affect households' decisions to acquire electricity technology. These effects are then assessed empirically by estimating beneficiaries' willingness-to-pay for electricity in three low-income countries that have pockets of households living in extreme poverty—Burkina Faso, Senegal, and Rwanda. Consistent with the theoretical model, the results indicate very low household willingness-to-pay for electricity access, and that willingness-to-pay diminishes as households' income declines. Therefore, the study recommends concentrating in the nearer term on ultra-low-cost decentralized off-grid solar technologies in programs to provide household electricity to the poor in rural areas.

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Willingness to Pay for Electricity Access in Extreme Poverty: Evidence from Sub-Saharan Africa

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1. Introduction

Electricity is an input for important public services, and improving electricity access in developing countries is a significant goal of the international community. The Sustainable Development Goals and the United Nations initiative *Sustainable Energy for All* (SE4All), for example, call for providing household electricity service to the 1.1 billion hitherto non-electrified people worldwide by 2030. Many of these people live in extreme poverty, making a living on less than $1.90 per person per day. Public investment requirements for this endeavor, however, are very high. For Africa alone, achieving the universal access goal is anticipated to cost no less than 31 billion USD per year (IEA 2017), which is equivalent to 70 percent of the continent's total official development assistance influx (WDI 2018).[1] The extent to which such costs are justified by anticipated economic and human development effects is unclear and a matter of ongoing debate (Peters and Sievert, 2016, Chaplin et al., 2017, Lenz et al., 2017, and Lee et al., 2019).

These concerns have spurred a growing interest in how off-grid solutions, such as solar-charged lanterns and small-scale solar photovoltaic (PV) home systems, can improve electricity access in rural areas (World Bank, 2018). These off-grid solar technologies can provide sufficient electricity for improved lighting, access to mass media, some limited use of high-efficiency appliances, and battery charging to households in rural areas at substantially lower costs than the traditional approach to increasing household electricity, expanding the national electricity grid. Off-grid alternatives also are more affordable than small diesel-powered generators historically used to compensate for unreliable grid supplies (Foster and Steinbuks 2009). Households and businesses that live under the grid and cannot afford a grid connection because of e.g., high connection charges (Golumbeanu and Barnes 2013) may also prefer that option.

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[1] These estimates do not account for additional costs of maintaining the grid infrastructure, which likely exacerbate existing deficits faced by poorly functioning utilities in many Sub-Saharan African countries (Trimble et. al., 2016).

At the same time, grid electricity access is an important input for the production of many important public services, which increase households' well-being through improved access to education, health care, public safety, and other services. If the aggregate gains to households from improving these public services are high, subsidized grid electrification to improve community electricity access may be desirable from a social planner's perspective. Additionally, improved electricity access at higher voltages for businesses may increase economic activity and welfare.[2] Both of these issues are beyond the scope of this paper.

This paper contributes to this important policy discussion by analyzing the willingness-to-pay (WTP) of poor households in rural areas for different types of electricity access. We first develop a theoretical model to study how consumer preferences, operational and capital costs of electricity service delivery, as well as availability of power supply, affect poor developing country households' decisions to acquire (and thus willingness to pay for) electricity access using different technologies. Non-homothetic consumer preferences allow us to characterize the income effects of choosing different electricity access technologies. Specifically, we show that at low-income levels just above a subsistence threshold, households will find it optimal for their purposes to choose solar lanterns or small solar home systems. For households at higher income levels, costlier grid electricity access is typically optimal. Diesel generation can also be optimal for providing household electricity access if grid electricity is unreliable and the operational costs of running a generator are reasonably low. The model also allows for a theoretical characterization of the value of broader community-level and long-term benefits from electrification that would leave households indifferent between choosing between a grid and off-grid technology, for a given income level.

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[2] Especially over the long term, productive use of electricity is limited if individual solar systems are the primary source of electricity supply (Blimpo and Cosgrove-Davies, 2019). Higher voltage electricity from the main grid (or larger-scale mini grids) (along with other types of public capital) is essential for improving the productivity of the agricultural sector (Assunção et al., 2018), emergence of manufacturing firms (Rud, 2012), and structural transformation to service-oriented economies (Perez-Sebastian and Steinbuks, 2017).

We then assess these income effects empirically by estimating beneficiaries' WTP for electricity in three low-income countries with pockets of households living in extreme poverty - Burkina Faso, Senegal, and Rwanda. Using survey data from unelectrified rural areas in each of these three countries collected between 2010 and 2013, we calculate stated WTP for different electricity access technologies, such as a solar lamp, a solar home system, and a grid connection. We then analyze its determinants by regressing stated WTP on the household income level, household characteristics, and other control variables.

We find that households put a high priority on having electricity and are willing to dedicate more than 10 percent of their monthly expenditures to paying for electricity. Consistent with the theoretical model, we also find that the household WTP increases with household income. A 1 percent increase in households' expenditures increases their WTP for electricity access by around 0.2 percent. Moreover, we see that the WTP increase with households' income is nearly twice as large for grid electricity than for a low-cost off-grid technology, such as a solar lamp.

Nonetheless, the overall WTP for electricity access by the rural households covered in the study is low enough that it is not sufficient in itself for covering operational and capital costs of extending on-grid electricity supply to poor rural households over the short- and medium-term. These results suggest concentrating efforts to bring electricity service to very low-income households in rural areas on ultra-low-cost off-grid technologies, such as solar lanterns and solar home systems. This recommendation is consistent with providing service that meets the basic needs of low-income rural households, as shown previously by Samad et al. (2013) and Grimm et al. (2017, 2018) in the context of solar home systems and even Pico-PV.

As noted above, if aggregate gains to households from improving provision of public services are high, subsidized grid electrification to improve community electricity access may be desirable from a social planner's perspective. Estimating indirect effects of grid electrification is beyond the scope of this paper. However, other studies find them too small to justify the extensive added cost for on-grid electrification (and maintenance of grid infrastructure) in remote poor areas, given the severe fiscal constraints faced by Sub-Saharan African countries (see e.g., Dinkelman 2011, Bernard 2012, Peters and Sievert 2016, Chaplin et al., 2017, Lenz et al., 2017, and Lee et al., 2019). In the longer term, the benefits of on-grid electrification become more desirable as households' incomes and productive opportunities grow due to a range of factors including, e.g., improved market access (Gollin and Rogerson, 2014, Blimpo and Cosgrove-Davies, 2019).

Our paper is part of a small but growing economics literature on demand for electricity access in developing countries. Lee et al. (2019) randomize different household connection fees across villages in Western Kenya to obtain households' *revealed* WTP for grid access, observing that adoption rates only increase modestly with decreasing fees. They conclude that the benefits people obtain from household electricity access to the grid (as revealed by their WTP) do not justify the high investment costs of expanding grid access, implying that expanding grid access for households might even produce negative social surplus. Blimpo et al. (2018) estimate a model of household and utility behavior, in which households choose their energy source and consumption quantity, and profit-maximizing utilities set connection charges. They similarly find that small willingness to pay for grid electricity access leads to low electrification rates. While these two studies are primarily concerned about grid electricity access, we also provide evidence on differences in the WTP for different types of electricity access technologies.

Our paper also relates to the recent literature on income effects of energy transition in developing countries. Wolfram et al. (2012) document that as poor households' incomes rise, their adoption of energy-using assets typically follows an S-shaped pattern, with the most rapid increases of ownership of energy-intensive appliances above the first threshold income level. Gertler et al. (2016) analyze household decisions to acquire energy-using assets in the presence of rising incomes. Similar to our paper, they develop a theoretical framework to characterize the effect of income growth on asset purchases and find that household demand for energy-using assets depends on the pace of income growth. Unlike our paper, where income effects of households' willingness to pay for electricity access are driven by non-homothetic preferences, Gertler et al.'s (2016) results are largely driven by credit constraints.

The remainder of the paper is structured as follows. Section 2 outlines the theoretical model of demand for electricity access technologies. Section 3 describes the contingent valuation design and the data collected in the three surveyed countries. Section 4 shows the results of econometric analysis including a set of robustness checks. Section 5 concludes.

2. Theoretical Model of Electricity Technology Choice

In this section, we first develop a simple tractable model of households' electricity technology choice. The objective is to show how non-homothetic preferences, operational and capital costs of technology, as well as structural characteristics, such as reliability of power supply, affect poor developing country households' decisions to acquire electricity technology. The salient feature of the model is the assumption that under extreme poverty, electricity use is only feasible after demand for other basic needs is met. When subsistence expenditures are met, the choice of electricity technology and the amount of consumed electricity services depends on standard parameters from the energy economics literature. The model allows us to characterize income effects of choosing between different electricity access technologies and determining the value of societal benefit from indirect effects of grid access that makes households indifferent between choosing between the grid and off-grid technologies for a given income level.

2.1. Assumptions

The economy comprises of representative consumers (households) with income M. For simplicity, we assume there are only two consumer goods and services: a subsistence good (food), f, and electricity services, $\tilde{e}$. Consumers derive utility from consumption of food and electricity services in the following manner:

$$U(f, e) = \alpha \ln(f - \bar{f}) + \tilde{e}\,, \tag{1}$$

where $\bar{f}$ is the subsistence level of food, and α is some positive scaling factor. The quasi-linear utility function guarantees that the subsistence good f is not subject to income effects, reflecting the necessity feature. Another important feature of this preference structure is that households have positive utility from the consumption of the subsistence good even with zero consumption of electricity in this subsistence economy. Food has a constant price, which, for simplicity is normalized to 1. Following Atkeson and Kehoe (1999), the consumption of electricity services comes from available

i) electricity *access* technologies that deliver the quantity of electricity, e, with probability π, which captures availability of power supply, and
ii) electricity *use* technologies, z, that cost p_z (per kW of electric power) and deliver services derived from electricity with the intensity factor v.[3]

The consumption of electricity services is thus given by

$$\tilde{e} = \min\left\{\pi e, \frac{z}{v}\right\}. \tag{2}$$

It is straightforward from equation (2) that the optimal utilization of electricity use technologies requires $z = v\pi e$. This is because if $\pi e > \frac{z}{v}$, the electricity in excess of z/v is wasted, and if $\pi e < \frac{z}{v}$, the electricity-using appliance is left idle. Assuming that households utilize these technologies optimally, we can rewrite equation (2) as

$$\tilde{e} = v\pi e. \tag{3}$$

We consider three electricity access technologies i that are common in many low-income countries. These technologies have important characteristics, which make the choice of each technology optimal under certain conditions. Technology 1 is a grid

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[3] For example, the LED light bulb produces lighting services with much lower electricity intensity than the incandescent light bulb.

connection. It has a high capital cost, k (costs of pole installation and wiring), medium operational (unit) cost, p (the tariff a utility charges per kWh), and medium availability, π (number of incidences and duration of power outages, which are very common in developing countries). Technology 2 is a diesel generator. It has medium capital costs (the acquisition cost of a generator), high operational cost (diesel and maintenance costs), and is always available.[4] Technology 3 is a solar home system. It has low capital costs (the acquisition cost of the solar home system), zero operational cost (as solar energy is free and maintenance costs are negligible and are thus ignored), and low availability (as the solar light is available only a limited number of hours per day). Additionally, both the diesel generator and the solar home system have limited electricity generation capacity, $\bar{e}$, and can thus deliver a limited amount of electricity. The solar home system has a particularly small generation capacity that is assumed lower than that of the diesel generator. We assume that the electric power supply from the grid connection is unlimited for household purposes. Table 1 summarizes the intrinsic features of each technology.

Table 1: Characteristics of electricity access technologies

Technology	**Capital Cost (k)**	**Operational Cost (p)**	**Availability (⚜)**	**Capacity ($\bar{e}$)**
Grid	High	Medium	Medium	Unlimited
Diesel generator	Medium	High	High	High
Solar home system	Low	Zero	Low	Low/Medium

In formal terms these assumptions can be summarized as follows: $k_1 > k_2 > k_3$; $p_2 > p_1 > p_3 = 0$; $\pi_3 < \pi_1 < \pi_2 = 1$; $\bar{e}_3 < \bar{e}_2 < \bar{e}_1 = \infty$, $i = \{1, 2, 3\}$.

For each chosen electricity access option $i = \{1, 2, 3\}$ the household thus faces the following problem:

$$\max_{f,e} U(f, v\pi_i e), \text{ s.t.,} \qquad (3)$$

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[4] This assumption implies there are no shortages of diesel and spare parts.

$$\lambda : \ f + k_i + (p_i + p_z)e \leq \ M, \tag{4}$$

$$\mu_i : \ e \leq \bar{e}_i, \ i = 2{,}3, \tag{5}$$

where λ and μ_i are the Lagrange multipliers. Inequality (4) is the standard household budget constraint. Inequality (5) is the electricity availability constraint, which states that the amount of consumed electricity cannot exceed the maximum amount of electricity the technology can produce. As grid electricity supply is unlimited, the electricity availability constraint (1) is always slack for this technology.

2.2. The optimal households' choice of electricity access technologies

The problem can be solved in two stages. We first solve for the optimal consumption of food and electricity (denoted by f^* and e^*, respectively) for each given electricity access technology *i*. We then compare these solutions to determine when each technology is optimal to choose. The consumer will choose the technology *i* if

$$U_j(f^*, e^*) > U_{i \neq j}(f^*, e^*) \ \forall \ i, j = \{1,2,3\}. \tag{6}$$

The first stage derivations are trivial using standard Lagrangian techniques and are shown in the Appendix. The second stage comparisons are described below.

Let us first start with comparing the grid connection versus the diesel generator choice. In doing so, we need to consider two separate subcases: when the capacity of the diesel generator does not bind, and when the capacity of the diesel generator does bind. Below we focus on the former subcase, as even a small diesel generator is typically sufficient to meet the energy needs of a household living in extreme poverty.[5] The latter subcase is shown in the Appendix. The household prefers the grid connection to the diesel generator (and thus has higher WTP for the grid connection) if

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[5] The capacity of diesel generators in Sub-Saharan Africa ranges between 0.5-2.5kW. This has sufficient capacity to meet consumer demand for basic electric services consumed by poor households, such as e.g., electric lighting, using radio and TV, and charging a mobile phone.

$$\alpha \ln\left[\frac{p_1+p_z}{(p_2+p_z)\pi_1}\right] + \frac{v[\pi_1(p_2+p_z)-(p_1+p_z)](M-\bar{f})}{(p_1+p_z)(p_2+p_z)} > \frac{v[\pi_1(p_2+p_z)k_1-(p_1+p_z)k_2]}{(p_1+p_z)(p_2+p_z)}. \qquad (7)$$

Now, let us compare the grid connection versus the solar home system. The household prefers the grid connection to the solar home system if

$$\alpha \ln\left(\frac{\alpha(p_1+p_z)}{v\pi_1(M-p_z\bar{e}_3-k_3-\bar{f})}\right) + \frac{v\pi_1}{p_1+p_z}\left(M-\bar{f}\right) > \alpha + v\left(\frac{\pi_1 k_1}{p_1+p_z} + \pi_3\bar{e}_3\right). \qquad (8)$$

Finally, let us compare the diesel generator versus the solar home system. The household prefers the diesel generator to the solar home system if

$$\alpha \ln\left(\frac{\alpha(p_2+p_z)}{v(M-p_z\bar{e}_3-k_3-\bar{f})}\right) + \frac{v}{p_2+p_z}\left(M-\bar{f}\right) > \alpha + v\left(\frac{k_2}{p_2+p_z} + \pi_3\bar{e}_3\right). \qquad (9)$$

The first term on the left-hand side (LHS) of inequalities (7), (8), and (9) captures the utility change due to *the substitution* effect of electricity consumption for food. The second term on the LHS of these inequalities shows the utility change due to residual *income* effect. The term on the right-hand side of inequalities (7), (8), and (9) illustrates the utility change due to differences in capital costs and capacities.

Finally, observe that if

$$M \leq k_3 + p_z\bar{e}_3 + \bar{f} = M_0, \qquad (10)$$

no electricity supply option will be chosen.

2.3. The effect of household income changes on their electricity access technology choices

Inequalities (7)-(9) allow us to determine how changes in the household's income affect electricity access technology choice. Differentiating the left-hand side of these inequalities with respect to income we see that an increase in the household's income makes it more likely to prefer (thus increasing its WTP for) the grid connection to the diesel generator if

$$\pi_1(p_2+p_z) > p_1 + p_z. \qquad (11)$$

As the operational cost of diesel generation, p_2, is assumed to be higher than the cost of grid electricity, p_1, this inequality holds as long as the availability of the grid power supply, π_1 is large enough not to offset the operational cost differentials of the diesel generation and the grid power supply.

Similarly, we observe that an increase in the household's income makes it prefer the grid connection (or the diesel generator) to the solar home system if the following inequalities hold:

$$M - \bar{f} > \frac{\alpha(p_1+p_Z)}{v\pi_1} + p_Z\bar{e}_3 + k_3, \tag{12}$$

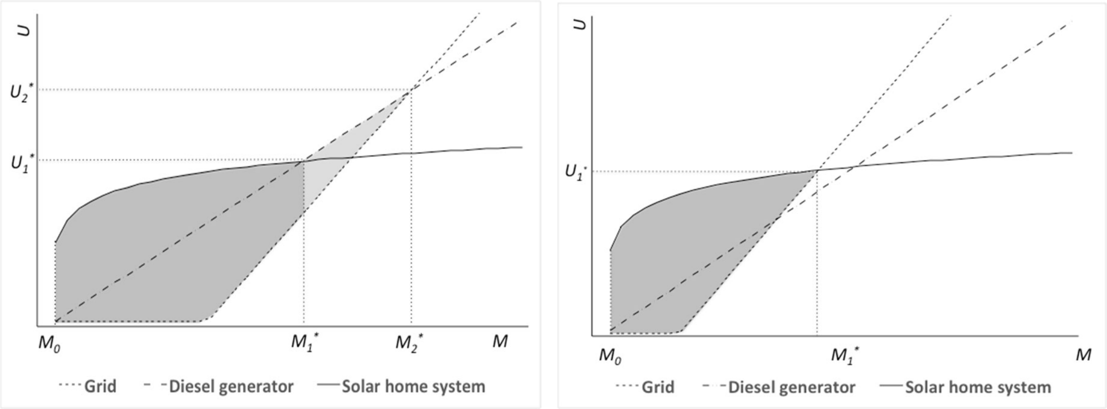
for the grid connection, and

$$M - \bar{f} > \frac{\alpha(p_2+p_Z)}{v} + p_Z\bar{e}_3 + k_3, \tag{13}$$

for the diesel generator. Inequalities (12) and (13) imply that an increase in the household's income at the low-income levels make it prefer the solar home system to the grid connection (or the diesel generator) as this choice renders higher utility gain from the food consumption. The result is reversed when household income becomes high enough. The model thus establishes a relationship between the households' income and the electricity supply technology. Households find it optimal to choose the solar home system when their income is close to subsistence level, and the grid connection (the diesel generator) when their income is large enough and the quality of power grid supply is good (bad).

Figure 1 illustrates the relationship between households' income level and their valuation of electricity access technologies if the operational cost of diesel generation is higher than the cost of grid electricity, and grid supply is reliable. We know from inequality (11) that under these assumptions, households prefer the grid supply to the diesel generator at high-income levels. Panel a) of Figure 1 shows the subcase of households facing grid electricity connection charges that are high relative to the capital cost of the diesel generator, i.e., $k_1 >> k_2$. In this subcase, households find it optimal to acquire a solar home system at the low-income range $M \in (M_0, M_1^*]$, the diesel generator at the medium income range $M \in (M_1^*, M_2^*]$, and the grid connection at the high-income range $M > M_2^*$. Panel b) of the Figure 1 shows subcase of households facing electricity connection charges that are close to the capital cost of a diesel generator, i.e., $k_1 \gtrsim k_2$. In this subcase, households find it optimal to acquire a solar home system at the low-income range $M \in (M_0, M_1^*]$, and the grid connection at the high-income range $M > M_1^*$. In this subcase, the diesel generator is never optimally chosen.

Figure 1: Electricity Access Technology Value as a Function of Household Income



a) High grid connection charges

b) Low grid connection charges

Note. Shaded areas represent the break-even social values of electricity grid access vis-a-vis the solar home system (dark-gray area) and the diesel generator (light gray area).

2.4. Societal benefits of grid electricity

The analysis above focuses on decisions of individual households and thus ignores the fact that electricity services are also an essential input to the provision of public goods and services, such as education, health care, and public safety, as well as for improving income generation in the long term. Meeting electricity demand for provision of these public goods is difficult if not impossible with solar home systems and small diesel generators (Lee et al., 2016). Grid electricity access thus yields additional societal benefit and may be socially optimal even if other electricity access options are preferred at the individual household level. The break-even value of this benefit (and thus a subsidy for grid electricity access) for the continuum of households with the minimum income level M_0 is

$$E_1 = \int_{M_0}^{{M_1}^*} \left(U_3(f^*(M), e^*(M))dM - U_1(f^*(M), e^*(M))dM\right), \tag{14}$$

if the diesel generator is never optimal at the individual household level and

$$E_2 = \begin{array}{c} \int_{M_0}^{{M_1}^*} \left(U_3\left(f^*(M), e^*(M)\right)dM - U_1\left(f^*(M), e^*(M)\right)dM\right) + \\ \int_{{M_1}^*}^{{M_2}^*} \left(U_2\left(f^*(M), e^*(M)\right)dM - U_1\left(f^*(M), e^*(M)\right)dM\right) \end{array}, \tag{15}$$

if both the solar home system and diesel generator are optimal at the individual household level for certain income thresholds. If the realized societal benefit of grid electricity access is higher (lower) than that defined by equations (14) and (15), grid electrification subsidies achieve (do not achieve) welfare improvements. Using functional forms in this paper the break-even values of societal benefit of grid electricity access are given by

$$E_1 = \begin{array}{c} \alpha[(M_1^* - \mathrm{G})\ln(M_1^* - \mathrm{G}) - (M_0 - \mathrm{G})\ln(M_0 - \mathrm{G})] \\ +(\mathrm{C} - \alpha)(M_1^* - M_0) + \frac{D\left({M_1^*}^2 - {M_0}^2\right)}{2} \end{array}, \tag{16}$$

and

$$E_2 = \begin{array}{c} \alpha[(M_1^* - \mathrm{G})\ln(M_1^* - \mathrm{G}) - (M_0 - \mathrm{G})\ln(M_0 - \mathrm{G})] \\ +(\mathrm{C} - \alpha)(M_1^* - M_0) + \frac{D\left({M_1^*}^2 - {M_0}^2\right)}{2} + \frac{B\left({M_2^*}^2 - {M_1^*}^2\right)}{2} + A(M_2^* - M_1^*) \end{array}, \tag{17}$$

where *A, B, C, D,* and *G* are constants defined in the Appendix.

Figure 1 illustrates the break-even value of societal benefits of grid electricity access (with E_1 marked as dark shaded area and E_2 marked as light shaded area) for the subcases described above.

3. Empirical Evaluation of Household WTP for Electricity Access

To empirically test the model predictions, we use unique survey data from rural areas of three representative Sub-Saharan African countries with deep pockets of extreme poverty: Burkina Faso, Rwanda, and Senegal. The data were collected between 2010 and 2013 for impact evaluations on electricity access interventions. All three countries are among the world's poorest countries, classified as "low-income" by the World Bank, and had very low rates of electricity access, particularly in ultra-poor rural areas at the time the survey.[6] The surveyed areas correspond to subcase b) shown in Figure 1 as very few (if any) households in the sample use diesel generation. The analysis thus focuses on the determinants of WTP by rural households for solar generation and grid electricity access.

3.1 Data and Quantification of WTP

Identical WTP questions were asked in all three countries. Table 2 describes the basic information on the collected data sample.

In Burkina Faso, the data come from an impact evaluation of a Solar Home System electrification intervention in the rural province of Kénédougou supported by the Netherlands' Ministry of Foreign Affairs (see Bensch et al. 2013). For this purpose, a random sample in villages, drawn in 2010, was offered a solar home system (SHS) on a fee-for-service basis. The WTP survey was only elicited among households that did not have any electricity source at the time of the survey. Most of the remaining households had already had a private solar panel bought on local markets. Grid electricity was not available among the surveyed population.

In Rwanda, the 2011 data are a representative random sample of rural beneficiaries of the nationwide electrification project EARP (Electricity Access Rollout Programme, see Lenz et at., 2017 and Peters et al., 2014). All these households were hence located in rural areas where grid electricity had not yet been available. The

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[6] According to the World Bank Sustainable Energy for All (SE4ALL) database, rural electricity access in 2013 was 0.8% in Burkina-Faso, 7.7% in Rwanda, and 27.5% in Senegal.

vast majority of households (96 percent) did not have any electricity source.

Table 2: The data

	Burkina Faso	Rwanda	Senegal
Year of Data Collection	2010	2011	2011
Type of Sample	Non-electrified HHs in villages selected for electrification through Solar Home Systems[1] before intervention	A random sample of HHs in villages selected for electrification through grid extension before intervention	The random sample of HHs in villages selected for electrification through mini-grids
Location	Rural area with slightly above-average income opportunities due to cotton farming	National representative	Remote rural area, partly above-average soil fertility
Sample Size	553	1008	361
The share of HHs with electricity access	0	0.03	0.25[2]

Notes: [1] Households within these villages that already have a pre-electrification source (mainly solar panels) have been excluded. [2] Most common access technology in Senegal is a solar panel; there are also very few car batteries and generators.

The Senegal data are random samples of households in villages that the Senegalo-German Energy Access Program PERACOD[7] selected for electrification through solar-diesel village grids or Solar Home Systems (see Bensch et al. 2011). All the households were asked about their WTP for electricity services. A considerable share of households to be provided with grid electricity had already had a Solar Home System. The data in all countries provide detailed information about households' socio-economic situation and especially details on their electricity and energy sources, as well as expenditures, household appliances, and lighting patterns.

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[7] For more information on the program, see www.peracod.sn.

Table 3: Household statistics

Explanatory variables (standard deviation in parentheses)	**Burkina Faso** 2010 N_{max}=553	**Rwanda** 2011 N_{max}=1,008	**Senegal** 2011 N_{max}=361
Household			
Number of household members	8.3 (4.1)	5.0 (2.0)	12.2 (4.5)
Household head			
Female	<1%	15%	5%
Age	44.0 (13.2)	41.3 (13.5)	52.3 (13.9)
Years of education	1.7 (2.7)	5.1 (3.8)	6.1 (6.5)
Financial situation			
Household has a bank account	9%	54%	12%
Received a loan in last years	38%	20%	51%
—Formal loan	1%	15%	14%
—Informal loan	36%	5%	41%
Expenditures			
in constant 2011 USD	152 (248)	109 (184)	195 (238)
per capita, in constant 2011 USD	18 (19)	24 (41)	17 (22)
in constant 2011 international $ (PPP)	359 (587)	236 (398)	413 (504)
per capita, in constant 2011 international $ (PPP)	43 (46)	51 (88)	36 (48)

Notes: [1] improved building material refers to brick, stones, concrete, or tiles. [2] Improved roofing material refers mainly to zinc (Senegal) and iron sheets (Burkina Faso).

Sources: Senegal (2011), Burkina Faso (2010), Rwanda (2011).

Table 3 presents descriptive household statistics. Senegalese households are the largest with more than 12 members on average, followed by Burkina Faso (eight members), and Rwanda (five members). Most households are headed by men, with the share of female head of households higher in Rwanda (15 percent) than in the other two countries. Senegalese and Rwandan households tend to have slightly higher educational attainment (6 and 5 years, on average), compared to households in Burkina Faso (2 years).

Bank accounts are held by less than 20 percent of Senegalese and Burkinabe households. By contrast, more than half of Rwandan households have an account. This is also reflected in a relatively higher share of formal loan experience: 16 percent have received a loan from a commercial bank or a microfinance institution in the past 3 years. In Senegal and Burkina Faso, people rely more on informal credits, e.g. at a shop, from relatives or friends, or informal savings associations (tontines).

On average, total household expenditures—expressed in USD—are almost twice as high in Senegal as in Rwanda, and are also 14 percent higher than in Burkina Faso. Adjusting for purchasing power, these differences reduce to 80 percent and 3 percent, respectively. However, Rwandan households have the highest per capita expenditure in the sample and Senegalese households have the lowest. Comparing these values to national income data, this sample does not reflect the differences at the national level, where per capita income is highest in Senegal and lowest in Rwanda.[8] The Senegal sample is hence a relatively poorer sample than the Burkinabe sample and especially the Rwandan sample when compared to the overall population of the respective country.

Table 4: WTP electricity consumption levels

Scenario	Consumption level	Corresponds to SE4All access tier	Corresponds to technology
1	Electric lighting inside the house	< 1	Solar lamp
2	Electric lighting, radio, and TV, charging a mobile phone	2 or 3	Pico-PV kit/SHS
3	Electric lighting, radio, and TV, charging a mobile phone, fridge, electric stove	3 or 4	Grid connection

3.2 Contingent valuation design

In all three data sets, respondents were asked about their monthly WTP for one of

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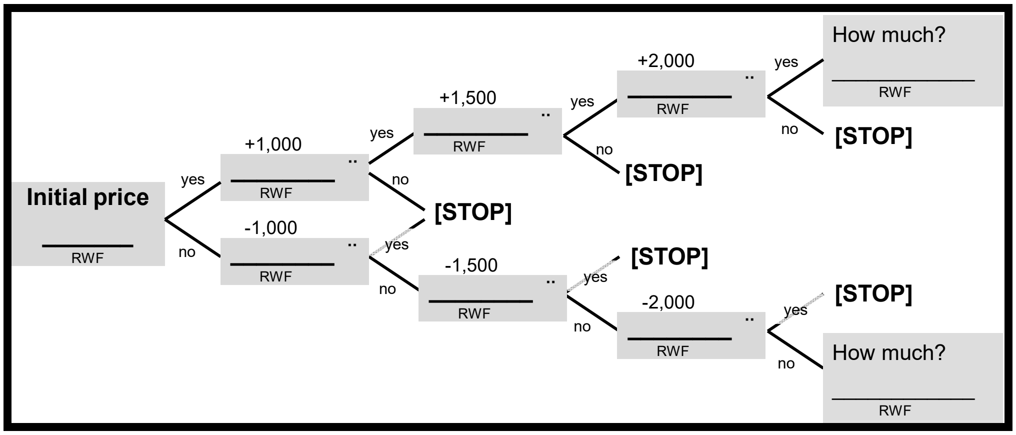
[8] According to World Bank data, GDP per capita in 2013 was 1,072 USD in Senegal, 684 USD in Burkina Faso, and 633 USD in Rwanda. Based on purchasing power parity (PPP), the 2013 figures become 2,269 international $ for Senegal, 1,634 $ for Burkina Faso, and 1,452 $ for Rwanda.

three randomly drawn hypothetical electricity consumption levels, which were identical in each survey. The three levels roughly correspond to SE4All's multi-tier access definition[9] and could be provided by different electricity access technologies. The three scenarios are displayed in Table 4.

Respondents were asked a dichotomous choice question ("Are you willing to pay each month amount X?") followed by a bidding game in order to elicit the highest accepted price. In order to reduce the hypothetical bias, respondents were reminded of their budget constraint and were told that their response would in no way influence the price at which the electricity service would actually be offered.

Figure 2: WTP bidding sequence



Note: 1000 RWF=0.17 USD

Source: Rwanda (2011) household questionnaire

The bidding sequence is illustrated in Figure 2, which is taken from the original questionnaire employed in Rwanda.[10] The full question can be found in the Appendix.

We use three alternative initial price bids in order to test for anchoring effects. The starting price was randomly drawn for each respondent. The starting prices were

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[9] Unfortunately, the consumption levels do not exactly mirror the different SE4All access tiers because they had not yet been defined at the time of the data collection in 2010 and 2011.

[10] In the Senegal survey, the same incremental amounts were used, albeit with different starting bids and, of course, a different currency. In the Burkina Faso baseline survey, the incremental amounts were +/- 1,000 CFAF, +/- 2,000 CFAF, +/- 4,000 CFAF.

adapted to the electricity prices in the respective future electrification intervention.[11] The instrument was validated during pre-tests and focus group discussions.

Table 3: Initial price bid for WTP elicitation (randomly assigned)

Burkina Faso	Rwanda	Senegal
10 USD	1.67 USD	6 USD
20 USD	8.35 USD	16 USD
40 USD	16.7 USD	26 USD

Sources: Senegal (2011), Burkina Faso (2010), Rwanda (2011).

3.3 Balancing across the randomly assigned electricity consumption levels

Each household was randomly assigned one of three electricity consumption levels. The randomization was done ad hoc by the enumerators in the field. Before entering a household, the enumerators drew one of three envelopes which contained the three electricity consumption levels and noted the drawn level on the questionnaire.

As can be seen in Table 4, the randomization produces three very similar groups, though some significant differences exist. Households that are assigned to the "grid electricity" consumption level tend to be slightly better off than those assigned to the "SHS" or "solar lamp" consumption level. The size of the differences is not very big in most cases and accordingly economically not significant. Nevertheless, our results should be viewed with acknowledgment of possible biases induced by this slight imbalance.

Table 4: Balancing across electricity consumption levels

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[11] Burkina Faso exhibits the highest price structure because the SHS fee-for-service included capital costs, unlike Rwanda and Senegal where the program covered capital costs.

	Mean			Difference		
	grid	SHS	solar lamp	grid vs. SHS	grid vs. solar lamp	SHS vs. solar lamp
Log of monthly expenditure in constant 2011 international $ (PPP)	5.41	5.24	5.04	0.17***	0.37***	0.2***
Expenditure quartile 2	0.23	0.24	0.27	-0.01	-0.04	-0.03
Expenditure quartile 3	0.23	0.27	0.24	-0.04*	-0.01	0.03
Expenditure quartile 4	0.31	0.26	0.20	0.05**	0.11***	0.06***
Rwanda	0.43	0.54	0.58	-0.11***	-0.15***	-0.04*
Senegal	0.25	0.17	0.17	0.08***	0.08***	0
Log of the initial bid in constant 2011 international $ (PPP)	3.39	3.12	2.65	0.27***	0.74***	0.47***
Number of household members	7.93	7.13	7.03	0.8***	0.9***	0.1
Head of household's age	41.74	42.19	41.11	-0.45	0.63	1.08
Head of household is a female	0.22	0.24	0.31	-0.02	-0.09***	-0.07***
Head of household has formal education	0.48	0.56	0.54	-0.08***	-0.06**	0.02
Household has a bank account	0.34	0.36	0.29	-0.02	0.05*	0.07***
Household has contracted formal credit	0.34	0.32	0.27	0.02	0.07***	0.05**
N	481	757	684	1,238	1,165	1,441

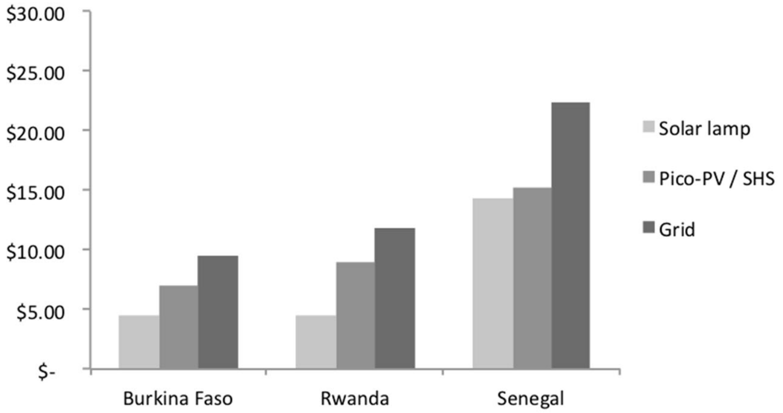
Note: *** $p<0.01$ ** $p<0.05$ * $p<0.1$ denote statistical significance.

4. Results

4.1 Households' Stated WTP

Figure 3 presents the WTP of households by country and electricity access technology. We can see that WTP increases in the intensity of electricity access technologies: households are willing to pay the most for the grid access ($9.6 to $22.3), followed by the small solar home systems ($7.1 to $15.3), and solar lamp ($4.5 to 14.3). In absolute terms, the average household WTP is higher in Senegal compared to the two other countries. [12]

Figure 3: WTP by electricity consumption level and country (in USD)



Sources: Senegal (2011), Burkina Faso (2010), Rwanda (2011).

When we express the WTP in relative terms, i.e., as the share of total household expenditures (Table), Senegal no longer stands out. In fact, households in Rwanda appear to have the highest relative WTP for electricity, willing to spend 14 percent of their total budget. The relative WTP is slightly lower in Senegal (12 percent) and Burkina Faso (10 percent). These results add to the robustness of our estimates, as they correspond to real-world electricity expenditures observed in rural areas (see, e.g., Lenz et al. 2017).

4.2 Determinants of household WTP

We test the predictions of the theoretical model by regressing the households' WTP on households' expenditures.[13] Table 8 shows the results of the baseline model

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[12] As we discuss in Section 3.3, households assigned to the grid electricity consumption level are slightly better off. We demonstrate theoretically in Section 2 and show empirically below that higher income levels are indeed associated with higher WTP for grid electricity. One may, therefore, suspect that the substantially higher WTP for grid electricity is driven by these income differences. However, the differences in household WTP are much larger than differences in wealth. For example, average monthly expenditures among the solar lamp group are around 7 percent lower than among the grid electricity group. By contrast, household WTP for solar lamps is 55 percent lower than for grid electricity.

[13] Recognizing the problem of potential measurement error in household expenditures, we also regress the households' WTP on households' asset index calculated based on households' reported ownership of durable appliances. The results reported in the Appendix are very similar.

(column 1), and sensitivity analyses with an additional set of controls (column 2), non-linear expenditures (column 3), and the interaction term between household expenditures and electricity technology.

Table 7: WTP as a share of the total household expenditure

	Burkina Faso	**Rwanda**	**Senegal**
Overall	0.12	0.15	0.13
— Solar lamp consumption level	0.06	0.12	0.11
— Pico-PV/ SHS consumption level	0.10	0.15	0.11
— Electricity grid consumption level	0.23	0.19	0.16

Sources: Senegal (2011), Burkina Faso (2010), Rwanda (2011)

Consistent with the theoretical model's predictions, we see that higher household income is associated with higher WTP for electricity access. In the base model specification, for example, a 1 percent increase in expenditures increases the WTP by around 0.2 percent (column 1). Estimated coefficients for country dummies show that the WTP is the highest in Senegal, followed by Rwanda. The household WTP is the lowest in Burkina Faso (the reference case). This result is consistent with the descriptive analysis in Section 4.1. Also consistent with the descriptive analysis in Section 4.1, the WTP generally increases with higher household electricity consumption levels. Furthermore, we can see that the WTP is clearly affected by the values of the initial starting bid.[14] The higher this initial bid, the higher the households' WTP. Most of the other household characteristics do not appear to have a clear influence on the estimated WTP (column 2). Only two household characteristics - the educational level of the head of household, and access to finance (measured by the availability of bank account) increase the WTP substantially. We also see that the addition of these controls has a very small effect on the size of the estimated coefficient for household expenditures. To account for potential

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[14] Remember that in each country, three alternative initial starting bids were randomly assigned to the households.

nonlinearities, we also regress WTP on household expenditure quartiles (column 3). Again, we see that that the wealthier a household, the higher is its WTP for electricity access, and the increase in the WTP is the highest for the wealthiest households.

Finally, we analyze the differential effect of expenditures on household WTP depending on the electricity consumption level by interacting WTP and the different consumption level scenarios (column 4). Consistent with the theoretical model, we see that the WTP increases significantly more with households' income for grid electricity than for a solar lamp. A 1 percent increase in households' expenditures increases their WTP for grid electricity by 0.23 percent. For a solar lamp, it increases only by half of that magnitude (0.12 percent). These effects are statistically significantly different. The increase in WTP for grid electricity with respect to households' income is also higher compared to SHS by 0.02 percentage points, however, the difference is not statistically significant.

Table 8: log of WTP in constant 2011 international $ (PPP)

	(1)	(2)	(3)	(4)
Log of household expenditures	0.229***	0.183***		0.230***
in constant 2011 international $ (PPP)	(0.025)	(0.028)		(0.044)
Distribution of household expenditures:			0.185***	
2nd quartile (1 = Yes)			(0.060)	
Distribution of household expenditures:			0.248***	
3rd quartile (1 = Yes)			(0.066)	
Distribution of household expenditures:			0.431***	
4th quartile (1 = Yes)			(0.073)	
Interaction:				-0.024
SHS#Log of household expenditures				(0.051)
Interaction:				-0.110**
Solar lamp#Log of household expenditures				(0.049)
Country: Rwanda (1 = Yes)	0.454***	0.237**	0.104	0.236**
	(0.091)	(0.106)	(0.105)	(0.105)
Country: Senegal (1 = Yes)	1.026***	1.091***	1.139***	1.098***
	(0.087)	(0.083)	(0.084)	(0.084)
Log of the initial bid	0.201***	0.185***	0.185***	0.188***

in constant 2011 international $ (PPP)	(0.029)	(0.029)	(0.029)	(0.029)
Scenario: Solar Home System (1 = Yes)	-0.212***	-0.222***	-0.226***	-0.088
	(0.051)	(0.052)	(0.050)	(0.283)
Scenario: Solar Lamp (1 = Yes)	-0.612***	-0.614***	-0.620***	-0.038
	(0.059)	(0.056)	(0.055)	(0.262)
Number of household members		-0.005	-0.006	-0.006
		(0.007)	(0.007)	(0.007)
Respondent's age		-0.001	-0.001	-0.001
		(0.002)	(0.002)	(0.002)
Respondent is female (1 = Yes)		-0.068	-0.072	-0.074
		(0.049)	(0.051)	(0.049)
Respondent's education:		0.120**	0.127**	0.118**
higher than primary school (1=Yes)		(0.055)	(0.055)	(0.055)
Household has a bank account (1=Yes)		0.242***	0.272***	0.245***
		(0.062)	(0.062)	(0.062)
Household contracted credit within last year (1=Yes)		-0.052	-0.038	-0.054
		(0.052)	(0.052)	(0.052)
Constant	0.601***	0.951***	1.752***	0.696***
	(0.190)	(0.203)	(0.170)	(0.264)
Observations	1,854	1,792	1,792	1,792
R-squared	0.308	0.318	0.315	0.320

Notes. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors are clustered on the village level.

4.3 Comparing Household Benefits and Costs of Service Provision

The results in section 4.2 clearly demonstrate that the household WTP for grid electricity increases with higher income and electricity demand. As households become wealthier, they put greater value on access to the grid, so that they can consume larger and more reliable amounts of electricity. Below we perform a simple cost-benefit analysis to determine whether the estimated magnitude of the difference in WTP for the different electricity access technologies is high enough to cover the difference in investment costs. In doing so, we divide the investment cost of electricity access technologies by the estimated households' monthly willingness to pay and obtain the hypothetical amortization period of the corresponding technology.[15]

For solar sources, the calculation is straightforward and intuitive. One could think of a fee-for-service arrangement where households pay for the fixed cost over several months. No additional direct costs occur (abstracting from maintenance costs, which are assumed to be small enough to be neglected) because electricity production is free. For the grid electricity, both the fixed and variable costs have to be borne by the household. Therefore, we add operational costs for a hypothetical consumption of 250 kW per year.[16] We assume no external cost of finance and thus do not include interest rates and loan service fees in calculations of the amortization period.

Table 9: Amortisation period

Technology	Approx. WTP electricity consumption level	Assumed investment costs in USD	monthly consumption fee	Amortization period in months		
				Burkina Faso	Rwanda	Senegal
Grid Electricity	level 3	1100	4.58	219	150	62
SHS	level 2	250	0	35	28	16
Solar Lamp	level 1	25	0	6	5	2

Note: Investment costs are based on World Bank (2009), EWSA (2012), and GOGLA and A.T. Kearney (2014). Monthly consumption fees assume an average consumption of 250 kWh per year and an electricity tariff of 0.22 USD per kWh. Amortization period is determined by dividing the investment cost of electricity access technologies by the estimated households' monthly willingness to pay.

Table 9 shows that amortization periods vary from 2 months for a solar lamp in Senegal to 219 months for a grid connection in Burkina Faso. In general, amortization periods seem reasonable only for solar lamps if the investment costs had to be entirely financed by the households. The relatively higher WTP for higher household income and consumption levels does not keep pace with the rapidly increasing investment costs of the higher-tier electricity access technologies. As point estimates

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[15] An alternative approach would be to calibrate and simulate the model described in section 2. This approach is, however, obscured by the lack of reliable estimates of some of the model's parameters, resulting in a loose calibration problem. We have, nonetheless, tried simulating the model for a range of plausible parameter values, and results were similar to the ones presented in this section.

[16] 250 kWh per year is the minimum electricity consumption defined by IEA (2011) for their Universal Access investment cost calculations.

in stated WTP approaches couldn't be obviously taken at face value, this very simple cost-benefit analysis has to be interpreted with some caution. This caveat notwithstanding it is nonetheless plausible to infer from our analysis that off-grid solar powered technologies are more likely to generate positive net private returns.

As discussed in the theoretical model above, this simple cost-benefit analysis does not account for the positive external effects of the grid access. Therefore, access to grid electricity may still be socially optimal. Given the large gap between costs and individual valuation for grid electricity, these benefits have to be substantial, and certainly exceed the ones found by the limited empirical evidence for the Sub-Saharan Africa region (Grimm et al., 2017; Lenz et al., 2017, Lee et al., 2019).

5. Conclusion

This paper contributes to the important policy discussion about improving household electricity access in low-income developing countries while keeping it affordable and financially viable. Our empirical findings for three Sub-Saharan African countries suggest that even poor households have a fairly high priority for access to basic electricity services and are willing to dedicate more than 10 percent of their monthly expenditures to electricity. At the same time, high costs of grid extension and low consumption levels of electricity by households in rural areas, especially among the poor, imply a need for highly subsidizing grid electrification as a means for increasing electricity access for rural households.

Our analysis underscores, both theoretically and empirically, the role of households' income as a critical driver for their electricity access decisions. At low-income levels close to subsistence level, households will find it preferable to choose ultra-low-cost electricity access technologies, such as small solar home systems, to meet their own electricity demands. As household incomes grow, grid electricity connection becomes a more attractive choice. Our empirical estimates suggest that a 1 percent increase in households' expenditures increases the WTP for electricity access by around 0.2 percent, and households are about two times as likely to prefer grid access to the solar lamp at higher income levels.

These results suggest that the best strategy for improving household electricity access in low-income countries requires combining short-term rural electrification efforts using ultra-low-cost off-grid technologies with a range of efforts for longer-term poverty reduction including investments in human capital and productive infrastructure. As households escape extreme poverty, income growth increases their WTP for electricity services, and on-grid electrification allows for better development potential in the longer run.

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Appendix

A1. Derivation of food and electricity consumption for different technology choices

For each choice of technology i let us write the Lagrangian function:

$$\mathfrak{L} = \alpha \ln(f - \bar{f}) + v\pi_i e - \lambda[f + k_i + (p_i + p_z)e - M] - \mu_i\,(e - \bar{e}_i). \qquad \text{(A1)}$$

Applying the first-order conditions (FOCs) yields:

$$\frac{\alpha}{f-\bar{f}} = \lambda, \qquad \text{(A2)}$$

and

$$v\pi_i = \lambda(p_i + p_z) + \mu_i, \qquad \lambda, \mu_i \geq 0. \qquad \text{(A3)}$$

Additionally, Kuhn-Tucker conditions imply that complementary slackness holds:

$$\lambda[f + k_i + (p_i + p_z)e - M] = 0, \qquad \text{(A4)}$$

and

$$\mu_i(e - \bar{e}_i) = 0. \qquad \text{(A5)}$$

Technology 1: Grid electricity

If the grid electricity technology is chosen, we know that capacity constraint (A5) does not bind (by the assumption that on-grid electricity supply is always sufficient to meet the household's demand for electricity services). Also, as preferences are well behaved, we know that the budget constraint (A4) always binds. Combined with complementary slackness this implies that $\lambda > 0$ and $\mu_1 = 0$. We can now obtain the closed-form solution for the optimal consumption of food and electricity by solving (A2) - (A5):

$$f^* = \frac{\alpha(p_1+p_z)}{v\pi_1} + \bar{f}, \qquad \text{(A6)}$$

and

$$e^* = \frac{M-\bar{f}-k_1}{p_1+p_z} - \frac{\alpha}{v\pi_1}. \tag{A7}$$

Observe that the consumption of food is fixed and independent of income. Electricity consumption is real residual income of food consumption. Finally, consumer utility is

$$U_1(f^*, e^*) = \alpha\left(\ln\left(\frac{\alpha(p_1+p_z)}{v\pi_1}\right) - 1\right) + v\pi_1\frac{M-\bar{f}-k_1}{p_1+p_z}. \tag{A8}$$

Technology 2: Diesel generator

If the diesel generator is chosen, we have to consider two subcases. In the first subcase, the diesel generation capacity constraint (A5) does not bind. Then $\mu_2 = 0$, and the solution is very similar to the grid electricity considered above (note that $\pi_2 = 1$):

$$f^* = \frac{\alpha(p_2+p_z)}{v} + \bar{f}, \tag{A9}$$

$$e^* = \frac{M-\bar{f}-k_2}{p_2} - \frac{\alpha}{v}, \tag{A10}$$

and

$$U_2(f^*, e^*) = \alpha\left(\ln\left(\frac{\alpha(p_2+p_z}{v}\right) - 1\right) + v\frac{M-\bar{f}-k_2}{p_2+p_z}. \tag{A11}$$

In the second subcase, the diesel generation capacity constraint (A5) does bind. Then, from equation (A5), $\mu_2 > 0$, and

$$e^* = \bar{e}_2. \tag{A12}$$

As preferences are well behaved, we know that the budget constraint (A4) always binds. This implies that $f + (p_2 + p_z)\bar{e}_2 + k_2 - M = 0$, and

$$f^* = M - k_2 - (p_2 + p_z)\bar{e}_2. \tag{A13}$$

The consumer utility in this subcase is given by

$$U_2(f^*, e^*) = \alpha\ln\left(M - k_2 - (p_2 + p_z)\bar{e}_2 - \bar{f}\right) + v\bar{e}_2. \tag{A14}$$

Technology 3: Solar electricity

If the solar electricity option is chosen, we know that its operating cost is zero ($p_3 = 0$), so the capacity constraint (A5) does bind, and

$$e^* = \bar{e}_3, \tag{A15}$$

As preferences are well behaved, we know that the budget constraint (A4) always binds. This implies that $f + p_z\bar{e}_3 + k_3 - M = 0$. We can now obtain the closed-form solution for the optimal amounts of food and electricity consumed by solving (A2) - (A5):

$$f^* = M - p_z\bar{e}_3 - k_3, \tag{A16}$$

and

$$U_3(f^*, e^*) = \alpha \ln\left(M - p_z\bar{e}_3 - k_3 - \bar{f}\right) + v\pi_3\bar{e}_3. \tag{A17}$$

A2. Derivation of the value of societal benefits of grid electricity

Using equations A8 and A14, let us define

$$\begin{aligned} &U_2(f^*, e^*) - U_1(f^*, e^*) \\ &\qquad = \alpha \ln\left[\frac{(p_2 + p_z)\pi_1}{p_1 + p_z}\right] + \frac{v[(p_1 + p_z) - \pi_1(p_2 + p_z)]}{(p_1 + p_z)(p_2 + p_z)} M \\ &\qquad + \frac{v\left[(p_1 + p_z)k_2 - \pi_1(p_2 + p_z)k_1 - \bar{f}\right]}{(p_1 + p_z)(p_2 + p_z)} = A + BM, \end{aligned}$$

where

$$A = \alpha \ln\left[\frac{(p_2 + p_z)\pi_1}{p_1 + p_z}\right] + \frac{v\left[(p_1 + p_z)k_2 - \pi_1(p_2 + p_z)k_1 - \bar{f}\right]}{(p_1 + p_z)(p_2 + p_z)},$$

and

$$B = \frac{v[(p_1 + p_z) - \pi_1(p_2 + p_z)]}{(p_1 + p_z)(p_2 + p_z)}.$$

Similarly, using equations A8 and A17, let us define

$$\begin{aligned} &U_3(f^*, e^*) - U_1(f^*, e^*) \\ &\qquad = \alpha \ln\left(\frac{v\pi_1\left(M - p_z\bar{e}_3 - k_3 - \bar{f}\right)}{\alpha(p_1 + p_z)}\right) - \frac{v\pi_1}{p_1 + p_z}M - \alpha \\ &\qquad + v\left(\frac{\pi_1(k_1 + \bar{f})}{p_1 + p_z} + \pi_3\bar{e}_3\right) = \mathrm{C} + \alpha\ln(M - G) + DM, \end{aligned}$$

where

$$C = \alpha\ln\left(\frac{v\pi_1}{\alpha(p_1 + p_z)}\right) - \alpha + v\left(\frac{\pi_1(k_1 + \bar{f})}{p_1 + p_z} + \pi_3\bar{e}_3\right),$$

$$D = \frac{v\pi_1}{p_1 + p_z},$$

and

$$G = p_z\bar{e}_3 + k_3 + \bar{f}.$$

Then

$$\int_{M_0}^{{M_1}^*}\left(U_3\left(f^*(M), e^*(M)\right)dM - U_1\left(f^*(M), e^*(M)\right)dM\right)$$

$$= \int_{M_0}^{{M_1}^*}(\mathrm{C} + \alpha\ln(M - G) + DM)dM$$

$$= \alpha[(M_1^* - \mathrm{G})\ln(M_1^* - \mathrm{G}) - (M_0 - \mathrm{G})\ln(M_0 - \mathrm{G})]$$

$$+(\mathrm{C} - \alpha)(M_1^* - M_0) + \frac{D\left({M_1^*}^2 - {M_0}^2\right)}{2}, \tag{A18}$$

and

$$\int_{{M_1}^*}^{{M_2}^*}\left(U_2\left(f^*(M), e^*(M)\right)dM - U_1\left(f^*(M), e^*(M)\right)dM\right)$$

$$= \int_{{M_1}^*}^{{M_2}^*}\left((A + BM)dM\right) = \frac{B\left({M_2^*}^2 - {M_1^*}^2\right)}{2} + A(M_2^* - M_1^*). \tag{A19}$$

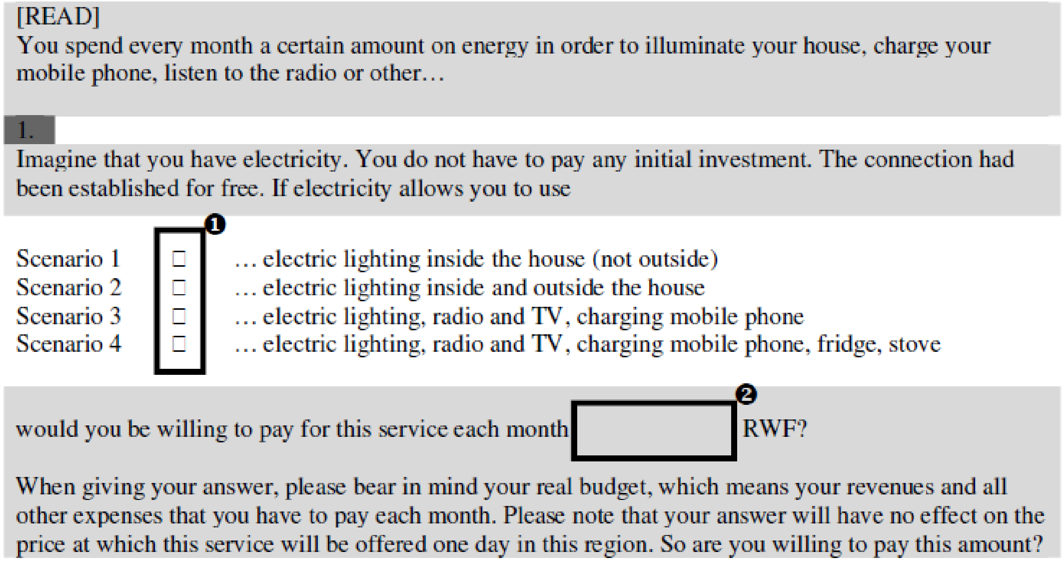
Using the results (A18) and (A19) in equations (14) and (15), we obtain

$$\begin{aligned} E_1 = {}& \alpha[(M_1^* - \mathrm{G})\ln(M_1^* - \mathrm{G}) - (M_0 - \mathrm{G})\ln(M_0 - \mathrm{G})] + (\mathrm{C} - \alpha)(M_1^* - M_0) \\ &+ \frac{D\left({M_1^*}^2 - {M_0}^2\right)}{2}, \end{aligned}$$

and

$$E_2 = \begin{array}{l} \alpha[(M_1^* - \mathrm{G})\ln(M_1^* - \mathrm{G}) - (M_0 - \mathrm{G})\ln(M_0 - \mathrm{G})] + (\mathrm{C} - \alpha)(M_1^* - M_0) \\ \qquad + \dfrac{D\left(M_1^{*2} - M_0{}^2\right)}{2} + \dfrac{B\left(M_2^{*2} - M_1^{*2}\right)}{2} + A(M_2^* - M_1^*) \end{array} .$$

A3. WTP Question



[READ]
You spend every month a certain amount on energy in order to illuminate your house, charge your mobile phone, listen to the radio or other…

1.
Imagine that you have electricity. You do not have to pay any initial investment. The connection had been established for free. If electricity allows you to use

❶

Scenario 1 ☐ … electric lighting inside the house (not outside)
Scenario 2 ☐ … electric lighting inside and outside the house
Scenario 3 ☐ … electric lighting, radio and TV, charging mobile phone
Scenario 4 ☐ … electric lighting, radio and TV, charging mobile phone, fridge, stove

❷

would you be willing to pay for this service each month ☐ RWF?

When giving your answer, please bear in mind your real budget, which means your revenues and all other expenses that you have to pay each month. Please note that your answer will have no effect on the price at which this service will be offered one day in this region. So are you willing to pay this amount?

❸

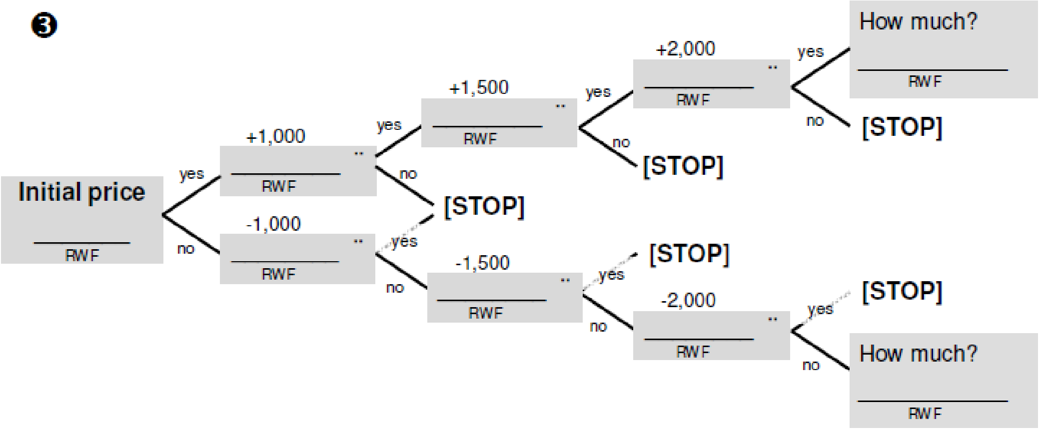


Table A4: log of WTP in constant 2011 international $ (PPP)

	(1)	(2)	(3)	(4)
Asset index	0.214***	0.183***		0.248***
	(0.024)	(0.026)		(0.039)
Distribution of asset index:			0.162***	
2nd quartile (1 = Yes)			(0.054)	
Distribution of asset index:			0.212***	
3rd quartile (1 = Yes)			(0.063)	
Distribution of asset index:			0.448***	
4th quartile (1 = Yes)			(0.075)	
Interaction:				-0.041
SHS#Log of household expenditures				(0.041)
Interaction:				-0.150***
Solar lamp#Log of household expenditures				(0.046)
Country: Rwanda (1 = Yes)	0.327***	0.118	0.126	0.106
	(0.088)	(0.102)	(0.101)	(0.101)
Country: Senegal (1 = Yes)	1.092***	1.160***	1.148***	1.165***
	(0.089)	(0.082)	(0.082)	(0.081)
Log of the initial bid	0.209***	0.190***	0.192***	0.188***
in constant 2011 international $ (PPP)	(0.029)	(0.030)	(0.030)	(0.029)
Scenario: Solar Home System (1 = Yes)	-0.228***	-0.231***	-0.231***	-0.226***
	(0.048)	(0.048)	(0.048)	(0.048)
Scenario: Grid Connection (1 = Yes)	-0.616***	-0.615***	-0.617***	-0.620***
	(0.060)	(0.056)	(0.056)	(0.055)
Number of household members		-0.009	-0.005	-0.010
		(0.007)	(0.007)	(0.007)
Respondent’s age		-0.001	-0.001	-0.001
		(0.002)	(0.002)	(0.002)
Respondent is female (1 = Yes)		-0.078	-0.075	-0.082*
		(0.049)	(0.050)	(0.048)
Respondent’s education:		0.130**	0.132**	0.132**
higher than primary school (1=Yes)		(0.054)	(0.054)	(0.054)
Household has a bank account (1=Yes)		0.235***	0.263***	0.236***
		(0.059)	(0.058)	(0.058)
Household contracted credit within last year (1=Yes)		-0.068	-0.060	-0.071
		(0.051)	(0.051)	(0.051)
Constant	1.836***	1.998***	1.751***	2.005***
	(0.132)	(0.180)	(0.179)	(0.177)
Observations	1,881	1,808	1,808	1,808
R-squared	0.316	0.324	0.320	0.328

Notes. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors are clustered on the village level.

The asset index aggregates information on housing characteristics (number of dwellings and rooms, plastering of the house, construction material of walls, roof, and floor), ownership of appliances (mobile phones, radios, and irons), of means of transportation (bikes, motorcycles, cars, and carts), as well as livestock (cattle, goats, and sheep)— into a single index, based on principal component analysis.