Energy for Sustainable Development 32 (2016) 121–129

Contents lists available at ScienceDirect

Energy for Sustainable Development

Insights from an energy poor Rwandan village

T. van Gevelt [a,*], C. Canales Holzeis [b], B. Jones [b], M.T. Safdar [a]

[a] Centre of Development Studies, University of Cambridge, 7 West Road, Alison Richard Building, West Road, Cambridge, CB3 9DT, United Kingdom
[b] The Cambridge Malaysian Commonwealth Education and Development Trust, c/o Trinity College, Cambridge, CB2 1TQ, United Kingdom

ARTICLE INFO

Article history:
Received 4 November 2015
Revised 22 February 2016
Accepted 9 March 2016
Available online 30 April 2016

Keywords:
Energy poverty
Rural development
Rural electrification
Rwanda
Sub-Saharan Africa

ABSTRACT

We used primary data collected from 163 households in an off-grid Rwandan village to provide insights into energy poverty at the household-level. Informed by the rural livelihoods literature, we constructed a novel asset- and income-based index to disaggregate our results by socio-economic status. We also employed microeconometric techniques to investigate the determinants of household willingness-to-pay for electricity. We found statistically significant differences between households of different socio-economic status for expenditure on lighting and other electricity services, willingness-to-pay for electricity, income-generating activities and food security. Overall, our findings suggest that initiatives aiming to end energy poverty and catalyze rural development should: (1) recognize the different potential impacts of policies on households of different socio-economic status; (2) be sensitive to energy stacking behavior; (3) take a holistic approach to rural development; (4) and ensure that households are able to access modern energy through flexible payment schemes and equitable and sustained improvements in income.

Introduction

Among the 17 Sustainable Development Goals adopted in September 2015 is the commitment to end energy poverty through ensuring “access to affordable, reliable, sustainable and modern energy for all.” This commitment to ending energy poverty is a crucial step towards achieving rural development and improving the livelihoods of the approximately 3 billion energy poor[1] individuals in the world today (Holmes et al., 2015).

Ending energy poverty and achieving rural development require stakeholders to make difficult choices on when, where and how to implement programs (Foley, 1992). As a result, concerted efforts by local communities and their champions, academics, the private sector, governments, NGOs and donor agencies are often hindered by a lack of primary data. While fully recognizing the uniqueness of each individual village and the broader macro-context in which it is embedded, an evidence-base of household data from energy poor villages can contribute to the drawing of stylized facts to help ensure that effective policies are put in place to end energy poverty and achieve rural development.

We contribute to the existing evidence-base for Rwanda (e.g. Bensch et al., 2011) and for sub-Saharan Africa (e.g. Kirubi et al., 2009) by analyzing primary data collected from 163 households in Rubagabaga village, Western Province, Rwanda to provide insights into energy poverty at the household-level. Specifically, we collected data on household energy use for lighting, cooking, enterprises and other electricity services, willingness-to-pay for grid electricity, as well as disaggregated gross income, education, health and food security. Informed by the rural livelihoods literature (e.g. Scoones, 2009; Charley and Walelign, 2015) we constructed an asset- and income-based index to disaggregate our results by socio-economic status. This has the added benefit of allowing for a better understanding of the impact of energy poverty and on the expected outcomes of future interventions on different segments of the village population. We also employed microeconometric techniques to investigate the determinants of household willingness-to-pay for (grid-level) electricity.

We found statistically significant differences between households of different socio-economic status for expenditure on lighting and other electricity services, willingness-to-pay for electricity, income-generating activities and food security. Overall, our findings suggest that initiatives aiming to end energy poverty and catalyze rural development will need to: (1) recognize the different potential impacts of policies on households of different socio-economic status; (2) be sensitive to energy stacking behavior; (3) take a holistic approach to rural development; (4) and ensure that households are able to access modern energy through flexible payment schemes and equitable and sustained improvements in income.

Energy poverty and rural development in Rwanda

Energy poverty has a negative impact on rural development at the household-level. This negative impact manifests itself both directly and indirectly and affects a household's ability to earn an adequate

* Corresponding author.

[1] The energy poor are defined as “…people who live on less than US$1.15 per day and have no access to reliable, safe and efficient energy for cooking, lighting, space heating and mechanical power…[and] who rely upon harmful energy like biomass-generated fire for their cooking and heating (Guruswamy 2011: 140).

http://dx.doi.org/10.1016/j.esd.2016.03.002
0973-0826/

Fig. 1. Rubagabaga.

Table 1
Distance from Rubagabaga to nearest facilities.
Source: Data obtained from authors' survey of village elders.

Facility	Distance	Travel time by most common mode of transportation*
Market	1 km	10 min
Bus stop	4 km	15 min
Police station	20 km	120 min
Primary school	2 km	40 min
Secondary school	3 km	60 min
Vocational school	6 km	25 min
Church	2 km	20 min
Health clinic	15 km	120 min
Hospital	35 km	90 min
Mill	1 km	10 min
Farmers' cooperative	3 km	20 min

* Modes of transportation include by foot, bicycle, motorbike and bus.

income, as well as their health, education, food security and quality of life (Zomers, 2003; Sovacool, 2012).

Contemporary (e.g. Kirubi et al., 2009) and historical case studies (e.g. Zomers, 2003; Bhattacharyya and Ohiare, 2012; Van Gevelt, 2014) have shown that ending energy poverty will only significantly benefit rural households when part of a holistic development approach. For example, good roads and built infrastructure, schools, and health clinics are required for rural households to be able to reap health, education and quality of life benefits. Similarly, agricultural extension and business support services are typically required to help households engage in new economic activities and to improve their economic output and productivity (Foley, 1992; Bastakoti, 2003; Cook, 2011).

Despite increasing urbanization on the back of sustained economic growth, the overwhelming majority (72%) of the Rwandan population continue to live in rural areas and are energy poor. The national electrification rate is currently 23% (Nyamvumba, 2015) with approximately 1.3% of rural Rwandans being connected to the grid in 2009 (WHO 2009). The majority of rural Rwandans use candles, kerosene driven wick lamps and, more recently, dry-cell battery driven LED torches/lamps[2] for their lighting needs. To date, there has been relatively low penetration of pico-solar lighting solutions (PLS) in rural Rwanda (Grimm et al. 2014). Many rural households own and use battery-powered radios and mobile phones which they charge externally at local village-based businesses (Manning et al., 2015).

Biomass, primarily firewood and charcoal, is the primary source of fuel for between 85% and 94% of the Rwandan population (Mazimpaka, 2014; Nyamvumba, 2015). In rural Rwanda, approximately half of all households use home-made traditional three-stone or mud-construction stoves. The other half of households use improved woodstove mud or ceramic cookstoves produced by local artisans. These improved cookstoves range from US$3–20 and vary greatly in terms of quality. As a result, there is wide variation in terms of efficiency gains and emission reduction (Global Alliance for Clean Cookstoves, 2012).

Rural electrification and the widespread adoption of improved cookstoves are regarded by the Rwandan government as essential components of a larger strategy to connect rural communities to economic opportunity through investment in infrastructure, skills development, and extension service provision. Specifically, the country's second Economic Development and Poverty Reduction Strategy (EDPRS 2) aims to extend grid coverage to rural areas, serve 22% of rural households through off-grid solutions, ensure that 100% of schools and health facilities have access to electricity by 2018, and reduce the dependence on biomass for fuel by 50% by 2020 (Borchers and Annecke, 2005; Republic of Rwanda, 2013; Nyamvumba, 2015).

Methods

Study site

Rubagabaga[3] is an energy poor, off-grid village located in Binana Cell, Western Province (see Fig. 1). Established in 1930, the village is home to 314 households consisting of approximately 1238 people. Rubagabaga is relatively isolated (see Table 1) and is vulnerable to flooding and mudslides during the rainy season. The main lighting technologies in the village are kerosene lamps and dry-cell battery torches/lamps. The main cooking fuels are firewood and charcoal. The dominant livelihood strategy in the village is farming. Crops include: bananas, beans, cassava, coffee, maize, potatoes, rice, sorghum, soya beans, sweet potatoes, tomatoes and yams. The only agricultural products processed in the village are bananas, with the resulting banana beer being sold both within the village and at the nearest large market. Other livelihood activities include the rearing of livestock, collection of non-timber forest products, farm and non-farm employment, petty business, and public and private transfers (e.g. rental income, remittances). Like most Rwandan villagers, Rubagabaga's inhabitants regularly visit a nearby electrified market center and have a good grasp of electricity and its potential uses (Manning et al., 2015).

Data collection

Data were collected through a household survey. The household survey was based on the livelihoods framework (e.g. Scoones, 2009) and the World Bank's Living Standards Measurement Surveys (LSMS) (e.g. O'Sullivan and Barnes, 2007). The survey included questions on demographics, assets, disaggregated gross income, energy use for household-owned businesses, consumption, health, food security, education, energy access and use for lighting, cooking and other uses, and willingness-to-pay for grid electricity.

Design of the household survey was informed by a scoping trip to Rubagabaga village in March 2015 and a focus group discussion with village elders in May 2015. The survey was translated into the first language of the village population, Kinyarwanda, and field tested

[2] Dry-cell battery LED torches/lamps tend to cost between US$0.82 and US$4.95 with a battery running cost of approximately US$0.01 per hour (Grimm et al., 2014).

[3] Rubagabaga was selected for this study due to impending plans for electrification through a 300 kW run-of-river mini-hydro plant. This affords the opportunity to return in the future to better understand how access to electricity affects development outcomes in the village.

Table 2
Household yearly expenditure on lighting and other energy services.

	Low SES	Medium SES	High SES
Candles	US$7.14 ($n = 2$)	–	US$15.12 ($n = 3$)
Kerosene lamp	US$7.74 ($n = 19$)	US$8.40 ($n = 23$)	US$10.89 ($n = 26$)
Dry-cell battery-powered	US$4.16 ($n = 46$)	US$5.02 ($n = 48$)	US$9.30 ($n = 45$)
Pico-solar lighting system	–	US$3.66 ($n = 1$)	US$7.33 ($n = 3$)
Lighting total	US$6.79 (6.00%)	US$8.35 (3.90%)	US$14.63 (2.14%)
Radio	US$1.62 ($n = 14$)	US$2.05 ($n = 31$)	US$2.41 ($n = 39$)
Mobile phone charging	US$12.13 ($n = 6$)	US$10.92 ($n = 34$)	US$12.38 ($n = 40$)
Other services total	US$5.03 (3.70%)	US$9.45 (3.37%)	US$12.02 (1.94%)

Note: Pico-solar home system costs are calculated on the basis of an expected lifetime of 3 years. Numbers in parentheses for lighting total and other services total denote expenditure as a proportion of household gross income.

through a pilot study undertaken in nearby Sunzu[4] village in May 2015. The survey was enumerated to 163 randomly selected households in June 2015 by four experienced enumerators and a supervisor. Data were coded and inputted into MS Excel datasheets before being cleaned and analyzed using STATA/SE 11.2.

Data analysis

To better understand energy poverty at the household-level, we clustered households by a measure of socio-economic status (SES). We selected a hybrid asset- and income-based approach to calculate the socio-economic status index. This hybrid approach has advantages over a purely income-based measure due to income's transitory and seasonal nature (Collins et al., 2009). Our selection of household assets was informed by the livelihoods framework (Scoones, 2009). Among the selected asset variables (see Table S1) were three composite variables representing a household's housing situation, implements and financial assets. Formally, each composite variable was defined as:

$$A_i = \sum\nolimits_k f_k \frac{(a_{ik} - \overline{a}_k)}{s_k} \tag{1}$$

where a_{ik} is the value of asset k for household i. a_k is the mean and s_k is the standard deviation. We then used principle component analysis to create uncorrelated components, with each component being a linear weighted combination derived from the initial variables. To create each composite variable, the result was weighted by elements from the first eigenvector.

Following Adato et al. (2006) and Charley and Walelign (2015), we calculated the asset- and income-based index on the basis of the following regression model:

$$\frac{y_i}{z_t} = \sum_j \beta_j (A_{ij}) + \beta_h H + \varepsilon_i \tag{2}$$

where y_i is gross income[5] for household i and z_t is the monetary poverty line.[6] β_j represents the marginal contribution of asset j to the gross income of household i, and the vector of coefficients, β_h, represents household-specific attributes (see Table S1). To allow for sufficient degrees of freedom within each group, we segmented households into asset- and income-based tertiles. This resulted in three groups: low socio-economic status households, medium socio-economic status households and high socio-economic status households.

For our variables of interest (household energy use, willingness-to-pay, disaggregated gross income, education, health and food security) we tested differences between the mean household of each SES group for statistical significance. For continuous variables, a one way ANOVA test was run. Bartlett's test for equal variances, however, reported unequal variances in the sample for all continuous variables tested. To determine whether the one way ANOVA test was sufficiently robust to the violation of the equal variances assumption, we used the pattern of sample sizes and standard deviation found in the sample to perform Monte Carlo simulations. We then compared the resultant simulation results to the nominal results allowing for variables that were likely to exhibit a higher or lower expected rate of type 1 error to be isolated. For these variables, we calculated and used the Brown–Forsythe *F*-start test statistic (see Table S2). For categorical variables, we used Fisher's exact test statistic.

We used regression analysis to understand how household-specific explanatory variables affected a household's stated willingness-to-pay[7] (WTP) for grid electricity. We measured WTP across two measures: a one-off connection fee and monthly payments. Following Manning et al. (2015), we based our selection of explanatory variables on the theoretical discussion of the determinants of electricity demand. Our explanatory variables therefore included: household expenditure on lighting and other electricity services, hours studied per weeknight, the age and gender of the household head, household size and the household's socio-economic status asset index score. Exploratory analysis of household WTP and explanatory variables suggested a nonlinear relationship. Formally, variants of the following nonlinear least squares model were estimated:

$$Q(\theta) = \sum_{i=1}^{N} q_i(y_i, x_{i,}\theta) \tag{3}$$

where y_i is the willingness-to-pay expressed by household i, x_i is a vector of household-level explanatory variables for household i, θ is a parameter vector and $q_i(\cdot)$ is a scalar function. We used robust standard errors to allow for heteroscedasticity.

Results

Demographics

The mean age of household heads in our sample was 45 years, with a standard deviation of 17. The majority of household heads were male (64%). Twenty-three percent of male household heads had no formal education with 74% being educated to primary level and 3% having completed secondary education. Forty-two percent of female household heads had no formal education and 58% had completed primary

[4] The leadership at Sunzu village was known to the research group from a previous project. Given its close proximity to Rubagabaga, Sunzu was seen as an appropriate site for the piloting of the survey instrument.

[5] Gross income was used instead of net income due to the poor quality of data on total costs of income-generating activities. Gross income consists of three components: income from self-employment, wage income and transfers (Angelsen and Lund, 2011).

[6] The monetary poverty line for Rwanda used was US$162.12 (National Institute of Statistics of Rwanda, 2012).

[7] To enumerate household willingness-to-pay, we chose to prompt for willingness-to-pay immediately after asking respondents about their household expenditure on lighting and other electricity services. This meant that the monthly expenditure calculations were fresh in respondents' minds. We acknowledge the possibility of hypothetical bias inherent in stated preference techniques and therefore caution against the use of these results as representative of a larger population.

Table 3
Willingness-to-pay for grid electricity.

	(1)	(2)	(3)	(4)	(5)	(6)
Electricity use						
Lighting expenditure	0.010**	0.012***	0.003	0.008	0.008**	0.001
	(0.005)	(0.005)	(0.003)	(0.005)	(0.004)	(0.003)
Other services expenditure	0.062***	0.045***	0.012***	0.052***	0.040***	0.009
	(0.005)	(0.007)	(0.004)	(0.006)	(0.007)	(0.006)
Education						
Number of hours studied		0.454***	0.166***		0.437***	0.180**
		(0.114)	(0.052)		(0.125)	(0.089)
Household-specific						
Age			0.128***			0.010***
			(0.002)			(0.002)
Gender			−0.068			0.051
			(0.069)			(0.089)
Household size			0.068***			0.067***
			(0.016)			(0.017)
SES index			0.002			−0.006
			(0.008)			(0.009)
R^2	0.713	0.756	0.914	0.719	0.745	0.869
Observations	146	100	100	150	101	101

Note: Columns (1)–(3) have the natural logarithm of willingness-to-pay for a grid electricity connection as the dependent variable. Columns (4)–(6) have the natural logarithm of willingness-to-pay for monthly payments for grid electricity as the dependent variable. All estimations are calculated using robust standard errors.

education. The average household size was 5 members with the largest household consisting of 11 members.

Energy use

Household lighting and other electricity services

Households used four lighting technologies, with 34% of households having used more than one lighting technology (see Table 2). The dominant technologies for lighting were kerosene lamps and dry-cell battery driven torches/lamps, with a handful of households also making use of candles. Four households used pico-solar lighting systems.[8] Three of these households were categorized as being of high socio-economic status (SES) and one household as medium SES. Two of the systems (both for high SES households) were capable of charging a mobile phone and cost the households approximately US$28. The other two systems provided lighting only and cost the households US$11. Notably, three of the four households continued to use one other source of lighting (kerosene lamps or dry-cell battery driven torches/lamps) in addition to their pico-solar lighting system.

With the exception of candles and pico-solar lighting systems, energy technology use was fairly uniform across the three SES groups. Low SES households spent the least in absolute terms (US$6.79) on lighting per year but spent the most as a proportion of household gross income (6%). Medium SES households spent an average of US$8.35 per year (4% of household gross income) and high SES households spent US$14.63 per year (2% of household gross income). Mean household yearly expenditure on lighting was found to be statistically different among all three SES groups at the 1% significance level. As a proportion of gross income, expenditure on lighting was also statistically different among groups at the 10% level.

In addition to lighting, 93 (58% of) households powered radios and 89 (55% of) households charged their mobile phones. When breaking down radio and mobile phone ownership by SES group, however, notable differences arise. Thirty percent of low SES households owned and powered radios compared with 59% of medium SES households and 83% of high SES households. Differences are even more striking for mobile phones, with only 11% of low SES households having owned and charged mobile phones compared to 63% of medium SES households and 91% of high SES households.

All sampled households powered their radios using dry-cell batteries. Two households charged mobile phones using their PLS and three households charged mobile phones using PLS purchased for their household's business enterprise. The remaining households charged their mobile phones at businesses in the village at a rate of approximately US$0.14 per charge. For radio and mobile phone charging services, low SES households spent the least in absolute terms (US$5.03) but spent the most as a proportion of gross income (4%). Medium SES households spent US$9.45 (3%) and high SES households spent US$12.02 (2%). Mean household spending on other services was statistically different among SES groups at the 1% level. As a proportion of household income, we found no statistically significant difference between the mean household of each SES group.

Table 4
Household willingness-to-pay and ability-to-pay for grid electricity.

	Low SES	Medium SES	High SES
WTP (total)	US$62.06	US$58.84	US$81.95
WTP (payments only)	US$26.63	US$35.00	US$29.56
ATP	US$8.46	US$16.09	US$24.72

Household willingness-to-pay for grid electricity

Ninety-three percent of households expressed a willingness-to-pay (WTP) for a one-off connection fee to the electricity grid and 95% of households, a WTP for monthly payments for electricity from the grid. For the connection fee, low SES households were willing to pay an average of US$35.45 (16% of gross income), medium SES households US$23.79 (15% of gross income) and high SES households US$52.72 (6% of gross income). For monthly payments, low SES households were willing to pay an average of US$2.22 (13% of gross income), medium SES households US$2.91 (19.25%) ,and high SES households US$2.46 (4%) over a period of 12 months. There was a highly significant difference (at the 1% significance level) in mean WTP for a grid connection among SES groups but not for monthly payments.

Table 3 shows the nonlinear least squares regression estimates for the natural logarithms of household WTP for the one-off connection fee (columns 1–3) and for monthly payments (columns 4–6). Starting with household WTP for the connection fee, in our first specification (column 1) we find household expenditure on lighting and other services to be positively associated with a higher WTP at the 5% and 1% levels, respectively. Our second specification (column 2) includes the weighted number of hours studied by enrolled school children. We find that household expenditure on lighting and other services continues to be significant, this time both at the 1% level. The number of hours studied is significant at the 1% level and positively associated with WTP with a relatively large coefficient: 0.454. Our preferred specification includes a number of household-specific variables (column 3). In this specification, we find that lighting expenditure is no longer statistically significant. Expenditure on other services, however, continues to be significant at the 1% level. The number of hours studied continues to be significant at the 1% level, albeit with a much reduced coefficient: 0.166. Among household-specific variables, we find that age of the household head and household size are both positively associated with WTP and significant at the 1% level.

Moving on to household WTP for monthly payments (columns 4–6), we find that lighting expenditure is not statistically significant while other services expenditure is significant at the 1% level (column 4) in our first specification. In our second specification (column 5), other services expenditure continues to be statistically significant at the 1% level and lighting expenditure is now significant at the 5% level. Number of hours studied is significant at the 1% level with a relatively large coefficient: 0.437. In our preferred specification (column 6), both lighting

[8] A pico-solar lighting system is defined as having a generation capacity of between 0.1 and 10 W (Alstone et al., 2015).

Table 5
Household yearly expenditure on main cooking fuel source.

	Low SES	Medium SES	High SES
Firewood (purchased)	US\$118.71 ($n = 13$)	US\$70 ($n = 18$)	US\$149.80 ($n = 16$)
Firewood (collected)	284 h ($n = 48$)	325 h ($n = 51$)	285 h ($n = 45$)
Charcoal	US\$90.68 ($n = 1$)	US\$140.14 ($n = 4$)	US\$199.50 ($n = 5$)
Cooking total	US\$30.83 (11%)	US\$33.71 (10%)	US\$71.10 (9%)

*Cooking total excludes firewood that is collected by households.
**Numbers in parentheses for cooking total denote expenditure as a proportion of household gross income.

expenditure and other services expenditure are no longer statistically significant. Number of hours studied continues to be significant, but only at the 5% level and with a much lower coefficient: 0.180. Age of the household head and household size are both positively associated with WTP at the 1% significance level.

Using current expenditure on lighting and other electricity services as a measure of household's ability-to-pay (ATP), we assessed the extent to which household WTP and ATP matched up for the average household of each socio-economic group (see Table 4). Starting first with the total WTP for grid electricity for a year (including connection fee and monthly payments), we found that the average low SES household expressed a WTP of more than seven times their ATP. For medium and high SES households stated WTP was more than three times the average ATP. When only considering WTP for monthly payments (over 12 months), we found that the average low and medium SES households stated a WTP more than three times and two times ATP, respectively. The average high SES household, however responded with a stated WTP remarkably similar to the average household's ATP.

Household cooking

We found that 113 (69%) households used traditional stoves and 50 (31%) households used improved mud-woodstoves that they had purchased. We found no significant difference in distribution of traditional and improved mud-woodstoves among the three SES groups. The main fuels used in Rubagabaga were firewood and charcoal. Eighty-seven percent of households collected firewood themselves and 13% only purchased either firewood or charcoal. Thirty-two percent of households both regularly purchased and collected fuel with no significant difference in distribution among SES groups (see Table 5).

Low SES households spent the least (US\$30.83) on their main cooking fuel source but the most as a proportion of gross income (11%). Medium SES households spent US\$33.71 (10% of gross income) and high SES households spent US\$71.10 (9% of gross income) on their main cooking sources, respectively. We found no statistically significant differences between SES groups for expenditure on main cooking fuels. Medium SES households spent the most time collecting firewood (325 h yearly), followed by high SES households (285 h) and high SES households (284 h).

Energy use for business enterprises

From the 163 households surveyed, 16 operated their own business enterprises (see Table 6). All 16 enterprises were run by high SES households. Six enterprises were bars serving locally produced banana beer and alcoholic beverages purchased from the nearest market town. In addition to serving alcoholic beverages, three bars engaged in one or more of the following business activities: selling mobile airtime, charging mobile phones, and selling meat products. The primary energy source used by four of the bars was pico-solar lighting systems. Two of the systems were sufficient for lighting only. The remaining two systems were capable of charging mobile phones. In addition to using a PLS, one of the bars used candles as an additional lighting source. The two remaining bars used kerosene lamps, candles and firewood as their energy sources.

Five of the households operated restaurants. In addition to being restaurants, these restaurants all sold mobile airtime to customers. All five restaurants relied primarily on firewood for cooking, with one restaurant also using charcoal. For lighting, one restaurant used candles and three restaurants used kerosene lamps. One restaurant used both kerosene lamps and a pico-solar lighting system. Three households ran shops, with only one of these shops engaging in another business activity: charging mobile phones. For lighting, one shop used kerosene lamps and two shops used dry-cell battery-powered torches/lamps. Two households operated hair salons. One hair salon also charged mobile phones. Both hair salons relied primarily on lead-acid batteries. The hair salon that charged mobile phones also had a PLS capable of charging mobile phones.

When asked why they chose their bundle of energy sources for their business enterprises, respondents cited: easy availability ($n = 13$); affordability ($n = 11$); efficiency ($n = 2$); and a lack of alternative options ($n = 2$). When asked what challenges their businesses faced as a result of not having reliable grid-level electricity, respondents responded with: security (e.g. thieves); a limited ability to work into the evening; not being able to provide entertainment (e.g. television) for customers in bars and restaurants; being unable to keep meat and vegetables fresh and to serve cold beverages; and the inability to grow existing business activities and diversity into new business opportunities. Fourteen out of 16 respondents said that they would expand their current business activities and/or move into new business opportunities with electricity. New business opportunities cited by respondents included welding, textiles, carpentry, and agricultural processing. One respondent, however, replied that she did not think that her business would increase with access to electricity. Instead, she cited that the main barrier to attracting more customers was poor infrastructure connecting households within Rubagabaga and connecting Rubagabaga to other villages.

Development outcomes

Disaggregated gross income

Table 7 presents the mean disaggregated household gross income for each SES group. For all three groups we found that agriculture was

Table 6
Business enterprises in Rubagabaga.

Main business activity	Other business activities	Energy sources used
Bar ($n = 6$)	Airtime/Charging mobile phones/Butcher	Solar home system, firewood, kerosene, candles
Restaurant ($n = 5$)	Airtime	Firewood, charcoal, kerosene, candles, solar home system
Shop ($n = 3$)	Charging mobile phones	Kerosene, lead-acid batteries, solar home system
Hair salon ($n = 2$)	Charging mobile phones	Lead-acid batteries, solar home system

Table 7
Disaggregated household gross income.

	Low SES	Medium SES	High SES
Agriculture	US$150.40 (55.63%)	US$235.86 (54.80%)	US$716.78 (53.17%)
Non-timber forest products	US$1.30 (0.10%)	US$0.05 (0.02%)	US$23.28 (1.04%)
Livestock	US$16.40 (3.44%)	US$15.73 (2.30%)	US$112.71 (5.94%)
Farm employment	US$51.53 (24.16%)	US$47.11 (16.15%)	US$106.04 (9.55%)
Non-farm employment	US$15.00 (4.60%)	US$74.92 (10.40%)	US$55.52 (5.28%)
Own business activities	US$49.78 (11.28%)	US$112.77 (14.62%)	US$519.46 (24.73%)
Transfers	US$1.56 (0.57%)	US$3.82 (1.71%)	US$7.73 (0.28%)
Total	US$285.96	US$490.25	US$1541.51

the livelihood strategy that contributed most to household gross income for all SES groups. For low SES households, we found that agriculture contributed over half of gross income (56%) of which 61% consisted of subsistence[9] agriculture products. Medium SES households earned 55% of their gross income from agriculture (45% of which was derived from subsistence agriculture) and high SES households earned 53% of their gross income from agriculture (45% from subsistence agriculture). We found a statistically significant difference for the mean contribution of agriculture to household gross income among SES groups at the 1% level and a statistically significant difference among SES groups regarding the proportion of agricultural income derived from subsistence agriculture at the 5% level.

Non-timber forest products, primarily edible wild mushrooms harvested from the forest, contributed US$1.30 to low SES households (0.10%), US$0.05 (0.02%) to medium SES households, and US$23.28 to high SES households (1%). Low SES households derived US$16.40 (3%) of their gross income from livestock with medium SES households having earned US$15.73 (2%). High SES households earned US$112.71 (6%) from livestock. We found that differences in the mean contributions for SES groups were statistically significant at the 10% level for non-timber forest products and at the 1% level for livestock.

Farm employment was the second most important contributor to the gross incomes of low SES households (24%) and medium SES households (16%). High SES households derived 10% of gross income from farm employment. For low SES households, 18% of income derived from farm employment was received through in-kind payments. In-kind payments constituted 10% and 5% of farm employment of income for medium SES and high SES households, respectively. We found the mean contribution of farm employment to gross income for the three SES groups to be significantly different at the 5% level. As a proportion of income, mean differences between the three SES groups were highly significant at the 1% level. For low SES households non-farm employment contributed US$15 (5%) to household gross income, while the contribution for medium and high SES households was US$74.92 (10%) and US$55.52 (5%), respectively.

Own business activities was the second most important source of gross income for high SES households contributing US$519.46 (25%) to household gross income, and the third most important source of income for low and medium SES households, contributing US$49.78 (11%) and US$112.77 (15%) respectively. For medium and high SES households, the production and sale of banana beer accounted for 72% and 66% of own business activity income, respectively. For the mean household, we found statistically significant differences among SES groups for the contribution of own business activities both in absolute terms and as a proportion of household income at the 1% significance level.

Low SES households earned US$1.56 rental fees, remittances and public transfers. Medium SES and high SES households earned US$3.82 and US$7.73, respectively. This amounted to an average of less than 1% of gross income for low and high SES households and less than 2% for medium SES households.

Education

Out of a total of 287 school-aged children in surveyed households, 47 (16%) were unenrolled. Primary reasons for not being unenrolled cited by household survey respondents included: not being interested in school ($n = 17$), no financial means to continue education[10] ($n = 6$), failing the national exam ($n = 6$), finding school too difficult ($n = 5$), pregnancy ($n = 5$), illness ($n = 3$), taking care of siblings or ill parent(s) ($n = 3$), and working for money ($n = 2$).

On average, an enrolled child was absent from school for 2 days a month in low and medium SES households and for 1 day in high SES households (see Table 8). Reasons for enrolled children being absent from school included: illness ($n = 63$), heavy rain ($n = 12$), taking care of siblings ($n = 5$), going to market ($n = 6$), unavailability of school uniform on the day[11] ($n = 5$), not wanting to study ($n = 3$), and working for money ($n = 2$).

We found that enrolled low SES household children spent an average of 15 min studying per weeknight, with enrolled children at medium SES households studying for only 12 min per weeknight. Enrolled high SES children spent the most time studying each weeknight with an average of 23 min.

Health

Among our surveyed households, we found a total of 18 children with long-term illnesses. These included: respiratory illness ($n = 4$), parasites ($n = 2$), physical disability ($n = 3$) and malaria[12] ($n = 9$). On average, adults in low SES households were sick for 11 days a month and very sick for 8 days a month. For medium SES households, adults were sick for 8 days a month and very sick for 6 days a month. For high SES households, adults were sick for 9 days a month and very sick for 7 days a month (see Table 9). Symptoms of illness reported by household members included: malaria/cold and flu ($n = 126$), gastrointestinal problems ($n = 34$), physical injury ($n = 21$), tooth pain ($n = 7$), parasites ($n = 6$), chest pain ($n = 4$), pregnancy-related ($n = 3$), hepatitis C-related ($n = 2$), and HIV/AIDS-related ($n = 1$).

From the sample, only 9.2% of respondents stated that using kerosene lamps negatively impacted the health of their household. Households who answered positively cited the smoke from kerosene lamps as having caused respiratory and eye problems. In addition to kerosene lamps, a point was made by some households that dry-cell battery torches/lamps were detrimental to children's eyesight due to the poor quality of lighting. When asked if their main cooking fuel source negatively impacts the health of their household, 33% of households responded positively. Cited reasons included their main source of cooking fuel causing coughing, headaches, eye pain and breathing problems. Danger to children was also cited, both in terms of smoke being

[9] Following Angelsen and Lund (2011), subsistence agriculture products were included in the accounting of gross income through using prices derived from the household or through village averages.

[10] Education in Rwanda is free and compulsory for 6 years.

[11] Primary education in Rwanda is organized in two shifts. It is not uncommon for siblings to share school uniforms and stationery.

[12] Only includes cases where the child exhibited malaria symptoms at least 3 times in the past 12 months.

Table 8
Education.*

	Low SES	Medium SES	High SES
Total absences per month	2.288	1.762	1.460
Hours studied per weeknight	0.25	0.194	0.387

* Total absences is the measure of the average of the total number of absences for enrolled children per month weighted by the number of enrolled children in each household. Hours studied per weeknight is the average total number of hours studied per average school night for enrolled children, weighted by the number of enrolled children in each household per week.

harmful to children and the danger facing children when collecting firewood from the forest. The risk of a house catching on fire was also mentioned.

Regarding drinking water, the majority of households (31%) of households relied on a tube well/borehole. Other sources of drinking water used by households were piped water (28%), protected wells (19%), unprotected springs (14%), unprotected wells (5%) and surface water channels (3%). When asked about how drinking water is treated before being consumed, the majority of households (52%) boiled their water. Twenty-five percent of households used a water filter and 4% of households added bleach or chlorine tablets. Eighteen percent of households did not treat their water and 1% of households let the water stand and settle before drinking it. We did not find a statistically significant difference between treatments of drinking water among SES groups.

Food security

Fig. 2 shows the proportion of households who had inadequate food to fulfill their household's nutritional needs. For all three SES groups, the two growing seasons (March–May and August–November) saw dramatic increases in the proportion of households with inadequate food supplies. We further measured food security by calculating an index (0–1) that accounted for monthly changes in food availability for each household. A household with a score of 1 was food secure throughout the entire year. Food security was lowest for low SES households (0.656). Medium SES households and high SES households scored 0.704 and 0.788 on the index, respectively. There were statistically significant differences among mean households in each of the SES groups regarding the food security index at the 1% level.

The primary reason given by households for not having enough food during the year was the need to buy food from the market during the growing seasons and the high market price of staple food ($n = 123$). The inability of households to store enough food for the two growing seasons was reported by households to be a result of inadequate irrigation systems, having too little land to cultivate, using crops as seed inputs and inadequate storage capacity. Other reasons for not having enough food during the year given by households included being unable to find sufficient work to purchase food ($n = 9$), being unable to work the land due to illness or old age ($n = 3$), difficulty in getting to the market during growing seasons due to heavy rain ($n = 2$), and a shortage of firewood ($n = 1$).

Table 9
Health.*

	Low SES	Medium SES	High SES
Days sick per month (adults)	10.920	8.302	9.728
Days very sick per month (adults)	8.360	5.606	6.466

* Days sick per month is the number of days in a month where at least one household member was sick, weighted by the total number of household members sick. Days very sick per month is the number of days in a month where at least one household member was unable to work or undertake normal activities, weighted by the total number of household members very sick.

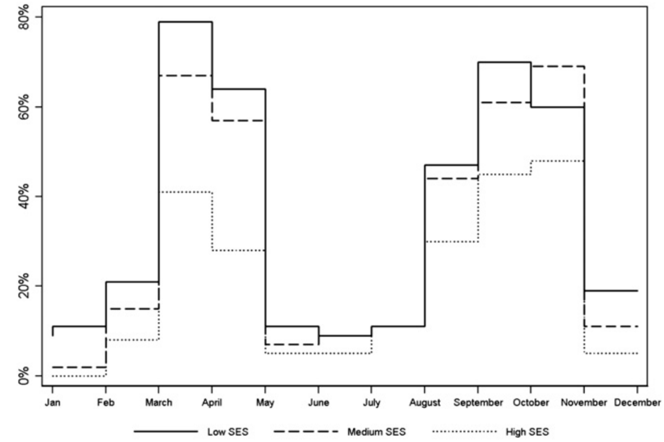

Fig. 2. Proportion of households with inadequate food supplies in Rubagabaga.

Discussion

Households in Rubagabaga village exhibit the characteristics associated with energy poverty in the literature: they are income poor, and suffer from poor education, health and food security outcomes. Households use a variety of incumbent lighting technologies, with over one-third of households stacking technologies. Other electricity services were limited to radio and mobile phones. Households used either firewood or charcoal as their main source of fuel. Approximately one-third of all households both bought their main source of fuel and collected firewood from the nearby forests. Cooking was undertaken on either home-made 3-stone cookstoves or on uncertified improved mud-woodstoves. Business enterprises run by 16 of the households tended to stack lighting and cooking technologies on the basis of availability, affordability, efficiency and a lack of alternative options. All business owners perceived notable challenges to their businesses due to energy poverty and 14 out of 16 expressed their ambition to expand and/or diversify their business activities with access to a reliable grid electricity supply.

Our data suggests a worrying discrepancy between household willingness-to-pay for (grid-level) electricity and ability-to-pay for low and medium SES households. Excluding the one-off connection fee, the average low SES household's WTP for monthly electricity payments was more than three times their ATP. For the average medium SES household, WTP was more than two times their ATP. Only for high SES households was the WTP similar to their ATP. Our regression analysis found that household WTP for the one-off connection fee and monthly payments was positively associated with the number of hours spent studying by children. Other statistically significant positive associations included household spending on lighting and other electricity services, the age of the household head and the size of the household. Somewhat surprisingly, we found that household WTP was not statistically significantly related to the household SES index score, and whether or not the household head was female.

Overall, our analysis of household data from Rubagabaga village suggests that initiatives aiming to end energy poverty and catalyze rural development will need to: (1) recognize the different potential impacts of policies on households of different socio-economic status; (2) be sensitive to energy stacking behavior; (3) take a holistic approach to rural development; (4) and ensure that households are able to access modern energy through flexible payment schemes and equitable and sustained improvements in income.

We found statistically significant differences between the average low, medium and high socio-economic status household for expenditure on lighting (absolute and as a proportion of gross income), expenditure on other electricity services (absolute), willingness-to-pay for grid electricity, sources of income and food security. These findings show the importance of recognizing the heterogeneous composition of households in energy poor villages and the importance of tailoring policy and initiatives accordingly. Failing to take into account the different socio-economic status of households within an energy poor village may have the unintended consequence of furthering inequality as a result of less wealthy households not being able to afford access to modern energy and lacking the scale and access to capital in, for example, agriculture and own business to make productive use of modern energy.

Household behavior in Rubagabaga provides further evidence for the need to design policies that are sensitive to energy stacking behavior rather than linear progression up the energy ladder (Kowsari and Zerriffi, 2011; Van der Kroon et al., 2013). For lighting, we found that over one-third of all households used more than one lighting technology and that three out of the four households that owned pico-solar lighting solutions continued to make use of incumbent technologies, such as dry-cell battery-powered torches/lamps and kerosene lamps. With less than one in ten households recognizing a negative linkage between kerosene lamps and health, shifts to modern energy will likely require behavioral nudges in addition to efforts to improve accessibility.

Households in Rubagabaga used either traditional cookstoves or uncertified, artisan-constructed improved mud-woodstoves. Both types of cookstoves are relatively inefficient and produce harmful emissions (Global Alliance for Clean Cookstoves, 2012). With more efficient artisan stoves costing approximately US$20 and gasifier stoves approximately US$40, it is unlikely that households in Rubagabaga would be able to afford these cookstoves without outside incentives. Due to the availability of fuelwood and only one in three households being aware of a negative impact on household health, the majority of households in Rubagabaga see little personal benefit to switching to improved cookstoves. Work by Barstow et al. (2014) further suggests that, even if households in Rubagabaga were given improved cookstoves, households would continue to use existing cookstoves for the cooking of staple foods that require longer cooking periods (e.g. beans) due to cooking preferences and when households only have wet firewood available for fuel.

Our results found that households in Rubagabaga village suffer from poor health, education, safety and food security outcomes. This suggests that initiatives aiming to end energy poverty and improve development outcomes should adopt a holistic approach. For example, in order for health outcomes to improve it is clear that households should switch from incumbent lighting and cooking technologies to reduce indoor air pollution and the incidence of associated respiratory diseases. Further improvements in health outcomes, however, would require complementary efforts beyond the provision of modern energy, whether through the construction and operation of a physical health clinic in Rubagabaga or through the development and facilitation of mobile health applications (Unwin, 2009). Another example is food security, with households in Rubagabaga unable to store enough food to consume during the two annual growing seasons. Households reported that this was, in part, due to inadequate irrigation systems, using crops as seed inputs and inadequate storage capacity. Access to modern energy, particularly electricity, is a prerequisite for irrigation systems, the use of farm machinery, and processing of crops; however it is also important for there to be complementary investment in the delivery of extension services to farmers to improve yields (Cabraal et al., 2005; Chang, 2009).

In order for households to reap the abovementioned health and food security benefits, it is important for households of all socio-economic statuses to be able to afford access to modern energy sources. Our results suggest that initiatives should be aware of the seasonal nature of income in energy poor villages, with most households in Rubagabaga reporting a lack of disposable income during the two agriculture growing seasons. Furthermore, in order for households to continue to take further advantage of modern energy, it is important for there to be a sustained and equitable increase in household income for all socio-economic groups. This would enable households to enter a virtuous cycle where households are able to afford and make productive use of modern energy. This could be achieved through a targeted approach that aims to add value to existing economic activities (e.g. agriculture, restaurants etc.) and help households diversify into new energy-enabled activities (e.g. carpentry, welding etc.). Our results suggest that, due to differences among socio-economic status groups, special efforts would need to be made to ensure that low- and middle-SES households benefit and are afforded the opportunity to learn new skills and access business development resources and capital. Furthermore, linkages should be built with external markets so that value flows into the village. If this is not the case, it is likely that the net result would be a redistribution of wealth within the village with no net positive welfare improvement.

Conclusion

We used primary data from 163 households in Rubagabaga village to provide insights into energy poverty at the household-level. Using a novel asset- and income-based disaggregation approach, we found statistically significant differences between households of different socio-economic status for expenditure on lighting and other electricity services, willingness-to-pay for electricity, income-generating activities and food security.

Our goal was to contribute to the development of an evidence-base from which to draw out stylized facts that can play a key role in ensuring that effective policies are enacted to end energy poverty and achieve rural development in Rwanda and, more broadly, sub-Saharan Africa. While fully aware of the uniqueness of each individual village, our results suggest that initiatives aiming to end energy poverty and catalyze rural development should: (1) recognize the different potential impacts of policies on households of different socio-economic status; (2) be sensitive to energy stacking behavior; (3) take a holistic approach to rural development; (4) and ensure that households are able to access modern energy through flexible payment schemes and equitable and sustained improvements in income.

Acknowledgments

We are grateful to Jonathan Berry, Jean-Paul Macumi, Brad Sanders, Dan Klinck and Harrison Masiga for their contributions during data collection and to John Holmes, Peter Dauenhauer and Damien Frame for their useful comments and Meredith Thomas for providing a map of Rubagabaga. We also thank the villagers of Rubagabaga village for their hospitality and for their valuable time. Data collection for this article was funded by the Cambridge Malaysian Education and Development Trust (CMEDT) and through a grant from the Templeton World Charity Foundation (TWCF). The opinions expressed in this article are those of the authors and do not necessarily reflect the views of CMEDT and TWCF.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2016.03.002.

References

Adato M, Carter MR, May J. Exploring poverty traps and social exclusion in South Africa using qualitative and quantitative data. J Dev Stud 2006;42:226–47.

Alstone P, Gershenson D, Kammen D. Decentralized energy systems for clean electricity access. Nat Clim Chang 2015;5:305–14.

Angelsen A, Lund JF. Designing the household questionnaire. In: Angelsen A, Larson AM, Lund JF, Smith-Hall C, Wunder S, editors. Measuring livelihoods and environmental dependence: methods for research and fieldwork. London: Earthscan; 2011. p. 107–26.

Barstow CK, Ngabo F, Rosa G, Majorin F, Boisson S, Clasen T, et al. Designing and piloting a program to provide water filters and improved cookstoves in Rwanda. PLoS One 2014;9(3).

Bastakoti BP. Rural electrification and efforts to create enterprises for the effective use of power. Appl Energy 2003;76:145–55.
Bensch G, Kluve J, Peters J. Impacts of rural electrification in Rwanda. Ruhr Economic Papers No. 284; 2011. p. 1–43.
Bhattacharyya, Ohiare. The Chinese electricity access model for rural electrification: approach, experience and lessons for others. Energy Policy 2012;49:676–87.
Borchers M, Annecke W. Poverty–environment–energy linkages in Rwanda. Policy Brief prepared for the United Nations Environment Programme by Sustainable Energy Africa; 2005.
Cabraal RA, Barnes DF, Agarwal SG. Productive uses of energy for rural development. Annu Rev Environ Nat Resour 2005;30:117–44.
Chang HJ. Rethinking public policy in agriculture: lessons from history, distant and recent. J Peasant Stud 2009;36(3):477–515.
Charley L, Walelign SZ. Assessing environmental dependence using asset and income measures: evidence from Nepal. Ecol Econ 2015;118:40–8.
Collins D, Morduch J, Ruthersford S, Ruthven O. Portfolios of the poor: how the world's poor live on $2 a day. New Jersey: Princeton University Press; 2009. p. 1–273.
Cook P. Infrastructure, rural electrification and development. Energy Sustain Dev 2011; 15:304–13.
Foley G. Rural electrification in the developing world. Energy Policy 1992;20(2):145–52.
Global Alliance for Clean Cookstoves. Rwanda market assessment: sector mapping. Accenture Development Partnerships; 2012. p. 1–70.
Grimm M, Muynehirwe A, Peters J, Sievert M. "A first step up the energy ladder? Low cost solar kits and household's welfare in Rural Rwanda. IZA Discussion Papers No. 2014; 8594:1–54.
Guruswamy L. Energy poverty. Annu Rev Environ Resour 2011;36:139–61.
Holmes J, Jones B, Heap B. Smart villages. Science 2015;350(6259):359.
Kirubi C, Jacobson A, Kammen DM, Mills A. Community-based electric micro-grids can contribute to rural development: evidence from Kenya. World Dev 2009;37(7): 1208–21.
Kowsari R, Zerriffi H. Three dimensional energy profile: a conceptual framework for assessing household energy use. Energy Policy 2011;39:7505–17.
Manning DT, Means P, Zimmerle D, Galvin K, Loomis J, Paustian K. Using contingent behavior analysis to measure benefits from rural electrification in developing countries: an example from Rwanda. Energy Policy 2015;86:393–401.
Mazimpaka E. Woodfuel in Rwanda: impact on energy, poverty, environment and policy instruments analysis. Int J Renew Energy Dev 2014;3(1):21–32.
National Institute of Statistics of Rwanda. The evolution of poverty in Rwanda from 2000 to 2011: results from the household surveys (EICV). Kigali: National Institute of Statistics of Rwanda; 2012. p. 1–40.
Nyamvumba R. Off-grid rural electrification in the republic of Rwanda. High-level workshop on off-grid village energy. Ministry of Infrastructure: Kigali; 2015.
O'Sullivan K, Barnes DF. Energy policies and multitopic household surveys: guidelines for questionnaire design in living standards measurement studies. Washington, DC: World Bank; 2007.
Republic of Rwanda. Economic Development and Poverty Reduction Strategy 2: 2013-2018. Kigali: International Monetary Fund; 2013. p. 1–32.
Scoones I. Livelihoods perspectives and rural development. J Peasant Stud 2009;36(1): 171–96.
Sovacool B. The political economy of energy poverty: a review of key challenges. Energy Sustain Dev 2012;16:272–82.
Unwin. ICT4D: information and communication technology for development. Cambridge: Cambridge University Press; 2009.
Van der Kroon B, Brouwer R, van Beukering PJH. The energy ladder: theoretical myth or empirical truth? Results from a meta-analysis. Renew Sustain Energy Rev 2013;20: 504–13.
Van Gevelt T. Rural electrification and development in South Korea. Energy Sustain Dev 2014;23:179–87.
Zomers A. The challenge of rural electrification. Energy Sustain Dev 2003;7:69–76.