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Off-grid energy services for the poor: Introducing LED lighting in the Millennium Villages Project in Malawi

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ABSTRACT

Lanterns that use light-emitting diodes (LEDs) powered by batteries, which are in turn charged by grid electricity or small solar panels, have emerged as a cost-competitive alternative to kerosene and other fuel-based lighting technologies, offering brighter light for longer duration at equal or lower cost over time. This paper presents lessons learned from the introduction of solar LED lanterns in rural Malawi. We discuss a market-based program using new and existing local commercial structures such as vendors and cooperatives to sell lanterns to village households without subsidy. The paper addresses issues of enterprise development, community interactions, and survey data on lighting use and expenditure patterns before and after LED lantern introduction. Households that purchased a lantern reported high levels of satisfaction with the LED lanterns as well as savings in annual kerosene expenditure comparable to the price of the lantern. These households also reported monthly incomes comparable to the price of the LED lanterns whereas non-adopters surveyed reported monthly incomes about half this level, suggesting a need for financing options to maximize adoption among poorer populations in rural areas. These results suggest that similar market based models of LED lighting technology dissemination have the potential to be replicated and scaled up in other off-grid regions in developing countries. However, viability of local cooperatives and supply chains for lantern products over the medium-to-long term remain to be assessed.

1. Introduction

Energy plays a critical role in economic development and poverty alleviation (Modi et al., 2006; Saghir, 2005). Nevertheless, 1.6 billion people in the world lack access to grid electricity (IEA, 2002). About 23% of sub-Saharan Africa's population is electrified, and only 5% of Malawi's households are connected to the grid (IEA, 2002). However, rural electrification rates are significantly lower than national figures suggest. In Kenya and Uganda, for instance, ~1% of rural households enjoy grid access (Karekezi, Kimani, 2004). Even households that are reached by national grids often receive intermittent and unreliable energy or are unable to pay for electricity altogether.

In the absence of reliable grid electricity, households across the developing world depend on kerosene, candles, biomass, and other non-electric sources for their lighting needs. These fuel-based lighting sources generate poor quality light at very low efficiencies (see Dutt, 1994; Mills, 2005; Van der Plas and de Graaff, 1988). Apart from lost productivity due to poor lighting, rural households face high recurring expenditures on fuel, sometimes reaching 25% of household budgets (Peon et al., 2005). For many rural households, obtaining fuel can be a time-consuming task that requires traveling long distances and is often undertaken by women and children (Batliwala, Reddy 2003; Laxmi et al., 2003). Fuel-based lighting is associated with soot, indoor air pollution (Peon et al., 2005) and burns. Furthermore, the consumption of fuel for lighting, equivalent to 1.3 million barrels of oil per day, results in carbon dioxide emissions on the order of 190 million tons per year. WLED [white LED] based illumination can reduce operating costs while increasing the quality and quantity of lighting service (Mills, 2005). LEDs are about four times more efficient than incandescent light bulbs, and can last up to 50,000 h (Steele, 2007). Features that make portable LED lanterns a potential substitute for kerosene-based lighting include durability, ability to direct light output, and low DC voltage and wattage levels which permit low-cost charging.

Previous generation solar home systems (SHSs) had high unit costs, often $350 or significantly more, and so achieved limited market penetration (Wamukonya, 2007; Urmee, Harries, 2009). Today, a 20 W SHS would include multiple components (solar panel, charge controller, mounting hardware, wiring, and typically a 600 Wh lead acid battery) at a total cost of approximately

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$250, and require technical support for installation and maintenance. In comparison, solar-powered LED lanterns would have wattages, storage capacities, and costs that are an order of magnitude lower, all packaged into a single unit costing $25–50. At these costs it becomes possible to reach a much larger population without the need for financially unsustainable donation programs or excessive market complexity (see Balint, 2006).

LED lanterns have been introduced in several developing country settings. Without attempting to be exhaustive, we take a note of a few of these programs. The Light Up The World Foundation (LUTW) has introduced over 16,000 primarily solar-powered LED lantern systems in several developing country settings, mostly through donation programs, but increasingly through market mechanisms like microcredit, and has shown a range of positive development outcomes to be associated with LED lighting (see Schultz et al., 2008). The organization's experience, quantified through life cycle analyses, indicates that, in comparison to pedal power and "pico hydro" systems, solar powered systems are best suited for sparsely populated rural areas (Bhusal et al., 2007). The Lumina Project has quantified the global costs of fuel-based lighting (Mills, 2005), tested the technical performance of commercially available LED lanterns (Granderson et al., 2008), and performed case studies introducing LED lighting in China (Jones et al., 2005), India (Apte et al., 2007a; Apte et al., 2007b), and Kenya (Mills and Jacobson, 2007; Radecsky et al., 2008; Johnstone et al., 2009; Johnstone et al. 2009). Other organizations, such as S^3IDF in India, have experimented with micro-enterprise development as a means of promoting LED lighting technologies (Rao et al., 2009). The World Bank Group's Lighting Africa initiative aims to support the global lighting industry in developing new technologies for off-grid regions through a variety of mechanisms (World Bank Group, 2008).

This pilot is focused on introducing LED lanterns in poor, rural areas using a market-based approach with an emphasis on capacity building among local commercial institutions such as cooperatives and vendors. The pilot was carried out in a cluster of villages near Mwandama in the Zomba district of southern Malawi, as part of the Millennium Villages Project (MVP), a multi-sectoral program to meet the Millennium Development Goals (see Sanchez et al., 2007; Sanchez et al., 2009). The impact of solar-powered lanterns on household lighting and kerosene purchase patterns was quantified using household survey data. We attempt to answer four interconnected questions to maximize the adoption of this technology by the poor. First, what are some aspects of a useful approach to commercial introduction of LED lighting technologies in rural developing country settings? Second, what impacts did LED lantern purchase have on household lighting patterns, especially expenditures on fuel lighting? Third, what distinguished households that purchased lanterns from those that did not? And finally, what practices could facilitate the broader dissemination of this technology?

2. LED Lantern introduction

2.1. Overview

The Millennium Villages Project (MVP) began in 2004 and currently encompasses approximately 400,000 people in 80 Millennium Villages across ten Sub-Saharan countries (Sanchez et al, 2007, Sanchez et al, 2009). The purpose of the Project is to achieve the Millennium Development Goals by 2015 in poor agricultural regions through science-based, community interventions across the sectors of agriculture, nutrition, health, water and sanitation, energy, infrastructure and ICT, and business enterprise development. Village interventions are aimed at increasing rural productivity to allow villages "to move towards self-sustaining economic growth" (Sanchez et al. 2009). The lead partners of the Project include the Earth Institute at Columbia University, Millennium Promise, and the United Nations Development Program.

The LED lantern trial falls within the set of energy interventions undertaken as part of the MVP infrastructure program. The purpose of the trial was to both accelerate adoption of improved lighting technologies as well as to develop the local institutions for a larger market-based approach that would be sustainable and ultimately self-financed. The program also endeavored to make electric lighting options, to the greatest degree possible, affordable to the lowest income households, "the poorest of the poor."

After identifying efficient, high-quality products, which then underwent basic testing in the laboratory, the Project facilitated the logistics of purchase and shipping of three varieties of LED lanterns from manufacturers (see Appendix A for description of the models). The Project supported the formation of a local cooperative by providing training to members and establishing bank accounts. "Working capital" in the form of in-kind donations of lanterns was transferred to the cooperative, which acted as a wholesaler. The cooperative then sold LED lanterns in smaller quantities to local vendors, who retailed the lanterns to villagers. In the initial phase, the Project provided assistance in estimating a "price build-up" for products, selecting and training vendors, and marketing lanterns to customers.

Table 1 summarizes the price buildup. The cooperative estimated its own "base cost" as the lantern's bulk price plus an estimated shipping and import cost of 25%. The cooperative then sold LED lanterns to vendors at this base cost plus an additional markup of 10% if vendors paid the cooperative for the lantern in a full cash payment, or 20% if vendors paid for the lantern on an installment basis. End users, the village retail customers, were offered three pricing options. First, villagers could purchase lanterns in a single full cash payment for the vendor's price plus a 10% markup. Second, villagers could purchase under an installment plan to be paid over a period of two to six months on a payment schedule to be arranged between the vendor and customer. Recognizing that the installment plan entailed additional effort of collecting payments and the risk of default, prices were set at the vendor's price plus 20%, providing a higher

Table 1
Price buildup for LED lanterns.

Cooperative cost		
Base price (bulk price + estimated shipping cost of 25%)		
↓		
Vendor price (vendor chooses one of two payment options)		
Cash: cooperative cost + 10% markup	Installment plan: cooperative cost + 20% markup	
↓		
Customer price (customer chooses one of three payment options)		
Cash: vendor price + 10% markup	Installment plan: vendor price + 20% markup	Rental plan: vendor price + 30% markup

return to vendors. Finally, in order to reach the poorest, a rental plan was envisaged in which vendors would earn a total of the vendor's price plus 30% over the estimated life of the lantern.

The final prices paid by villagers covered all costs: the per unit base price of lanterns when purchased in bulk from the manufacturer, transport costs, import duties, and a markup for each participant in the supply chain. Since both the cooperative and each vendor made a profit from each sale, village businesses had a stake in the sustainability of the program. The trial did not offer villagers a subsidy to purchase lanterns. By starting with a "full cost" approach, local awareness and demand for the product were allowed to grow in tandem with the development of the supply chain, without market distortions, allowing for an accurate evaluation of demand for future orders. Finally, this approach avoids difficulty in community relations if an initial subsidy is removed at a later date.

2.2. Community participation

In line with literature noting the benefits of community participation in development projects (e.g. Hoddinott et al., 2001) early efforts to engage the community influenced the program design. Focus groups and trainings emphasized the trial nature of the program and technology, and the need for flexibility and cooperation from all stakeholders including the cooperative, customers, vendors and the Project.

Vendor interviews assessed the capacity and willingness of shop owners to sell LED lanterns. Vendor selection criteria included good community standing, an established and secure shop which would be staffed daily, and a stable business with sufficient capital. Vendors were asked about topics such as sales of kerosene and other light sources (including seasonal patterns), vendors' use of lighting in their shops, sales of other higher priced products, the proportion of sales on credit, and the characteristics of customers with higher disposable incomes. Interviewers then described the benefits and costs of LED lighting relative to kerosene and other traditional light sources, specific characteristics of the three lantern models selected for the trial, the proposed business models and payment options, and how the lanterns represented an opportunity to sell a new product and increase income. In general, vendors faced limited competition, had secure shop structures, did not keep written records of sales and expenditures, and sold relatively low priced goods (the value of the highest priced items was less than 5% of the sale price of the lantern). Shop owners did not sell many electrical goods besides dry-cell batteries and small torches. Nonetheless, all vendors approached by MVP staff expressed interest in participating in the trial.

Some key steps in the pilot's approach helped secure "buy-in" and feedback from the broader community. First, before starting work with the community, a meeting was held with village chiefs to inform them about the lanterns and the pilot. This was followed by focus group meetings with the community members consisting of 9–16 men and 9–16 women during which men and women separately discussed their lighting patterns in terms of light sources, expenditures, duration of use, the principal activities using light, seasonal variations in purchase and use, and future preferences. The groups then came together to view demonstrations of the LED lanterns, which included showing the various light settings of each lantern in a dark room. Participants were also shown a chart with weekly and annualized kerosene expenditures in comparison to the cost of each LED model under the cash, installment, and rental plans.

Feedback from interviews and focus groups influenced the design of the program in several ways. One of the three lantern models was consistently favored by all focus groups, so the pilot proceeded by offering only this model for sale. Participants showed very low interest in renting a lantern, preferring ownership instead. Vendors opposed the rental option because they feared damage to the product. Consequently, the rental payment option was discarded. Villagers expressed willingness and ability to pay for a lantern in cash or installments, but villagers were largely unfamiliar with payment by installment and preferred that each payment period be left to agreement between individual villagers and vendors. Finally, feedback from the discussions with vendors and villagers was used to select three vendors deemed trustworthy by the community.

Vendors then participated in a training workshop which defined steps in the sales process and roles of all participants. A cooperative was established to act as a lantern wholesaler. Vendors would purchase lanterns from the cooperative, which they could also join. For each lantern purchase, vendors would decide whether to pay in cash or installments, sign a contract with the cooperative, make payments, and take delivery of the lanterns. Vendors were not permitted to sell lanterns outside the Millennium Village Project's target area and each household was permitted to purchase a maximum of 1 lantern. Customers would choose a payment plan, fill out a prepared contract template, make payments, and obtain the lanterns. MVP would monitor the entire process through surveys with villagers, vendor interviews, and close work with the cooperative.

Sensitization meetings attended by villagers and vendors helped market the LED lanterns by informing participants about the pilot, demonstrating technical features, and taking purchase orders. These meetings were held at dusk to demonstrate the higher light output from the lanterns compared to fuel-based lights. Project staff also compared the cumulative cost of kerosene lighting to the price of LED lanterns, emphasizing that the LED lantern would provide more light and would be sold with a small solar panel for charging at home at no additional cost. The team described major features of the battery, such as its estimated 10 h discharge cycle, approximate life span of 1–2 years, and replacement cost of about $2.00–$3.00.[1] Project staff then described the payment options, and concluded by facilitating lantern sales by providing contracts for customers and vendors to fill in and sign.

2.3. Initial lantern sales

Following the community interactions, an initial tranche of 54 lanterns was sold rapidly at full price, including all transport costs and markups for the vendors, with customers paying $29.78 in cash payments and $32.61 for the installment plan. A lighting survey was integrated into the initial sales effort in order to assess both the impact of LED lanterns on household lighting and the best methods for reaching poorer sections of the populace. We now turn to the major results of the survey, before proceeding to the details on sales expansion, capacity building efforts, broader financing mechanisms, and scale-up.

3. Household lighting survey and analysis

3.1. Data sources and methodology

The lighting survey was administered during initial lantern sales in July–September 2008. Locally trained enumerators read

[1] All currency values have been converted into US$ using an exchange rate of 1 USD=141.05 MWK, the rate on July 15, 2008, approximately the midpoint of the survey period.

out the questions, and recorded respondents' answers. The data from the paper surveys were entered into spreadsheets on site in Malawi, where initial cleaning and data checks were also conducted. Analysis was performed by the Earth Institute at Columbia University.

A total of 97 households participated in the survey, including 54 that purchased a LED lantern and 43 that did not. The first visit by the enumerator to the homes of lantern buyers occurred within one week of purchase. Respondents were asked to compare their lighting patterns in the week immediately before and immediately after lantern purchase. Because households were approached only after purchase, the accuracy of responses depended upon respondents' recall of conditions before lantern purchase. These same households were re-surveyed again three to five weeks later to assess the persistence of changes in lighting patterns. For comparison, randomly chosen households who did not purchase lanterns were surveyed during the same period. This surveying method contrasts with another study on the impact of solar photovoltaic lanterns in communities in western India, conducted by Agoramoorthy and Hsu (2009), which relied less on respondents' recall by surveying a set of households in advance, then surveying them again after loaning lanterns, which were subsequently purchased on installments.

This paper also reports data from the MVP baseline survey, a more comprehensive energy survey administered to 300 households in Mwandama during March 2007 as part of a multi-sector surveying effort undertaken by the Project. Here too, the relevant data on lighting patterns from the baseline energy survey were self-reported.

3.2. Lighting survey respondent information

Of the 97 respondents to the lantern survey, 45 (46.4%) were male and 52 (53.6%) female, while 59 (60.8%) were heads of household, and 37 (38.1%) were spouses of the head of household. One (1.0%) respondent was a child of the head of household. The average age of respondents was 40.1 years.

3.3. Basic household information

About 35,000 people inhabit the Millennium Villages cluster in Mwandama, Malawi. The vast majority of the approximately 7000 households are not connected to an electric grid. Table 2 illustrates the overwhelming dependence among these households on fuel-based light sources, specifically kerosene and candles, as reported in the baseline energy survey.

The 97 households participating in the lighting survey reported using kerosene for 2.9 h per day on average. These households spent an average of $0.61 per week or $2.61 per month on kerosene, and reported paying an average of $1.09 per liter of kerosene in the previous year. Monthly kerosene expenditure data are summarized in Figs. 1 and 2. Kerosene expenditures were fairly constant across incomes. Thus, kerosene expenditures declined as a share of household income as incomes rose in the sample, suggesting that kerosene meets a basic minimum need.

Table 2
Primary and secondary light source among households (n=300).

	Primary light source (%)	Secondary light source (%)
Kerosene	96.3	1.1
Electric grid	2.4	0.0
Candles	0.3	82.5
Other	1.0	16.4

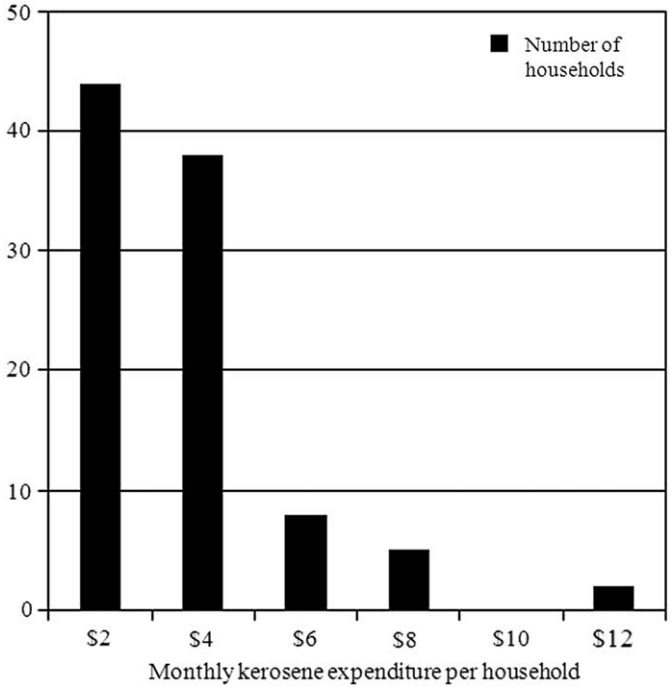

Fig. 1. Histogram of monthly household kerosene expenditures in US$ (n=97).

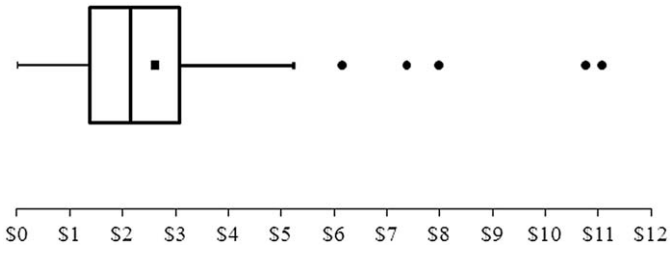

Fig. 2. Box plot of monthly self-reported kerosene expenditure per household in US$, showing minimum, mean, median, maximum, interquartile range and outliers (n=97).

The 97 households in the lantern survey reported using candles for 2.2 h per day, for a mean weekly expense of $0.38 or a mean monthly expense of $1.51. Spending on lighting from all sources including kerosene, candles, dry cell batteries, battery charging, rental fees, and other sources consumed 19.7% of household income, on average.

When households were asked to identify 3 activities for which light was the most important, the majority cited household activities like eating (30.9%), cooking (17.9%), and preparing for sleep (13.0%). Among the remainder, 11.1% of responses cited children's study, 6.8% reading, and 1.9% income generation.

3.4. Changes in lighting patterns after LED lantern purchase

LED lantern purchase had a dramatic impact on households' reported lighting use, as shown in survey results in Fig. 3. Of 54 households which purchased an LED lantern, 53 (98.2%) reported using kerosene for lighting in the week immediately before LED lantern purchase, while 34 (63.0%) used candles, and 27 (54.0%) used other lighting sources including dried grass. In the week after lantern purchase, only 29 households (53.7%) used kerosene, 2 (3.7%) used candles and 11 (24.4%) used other sources apart from kerosene, candles, and LED lighting. When households

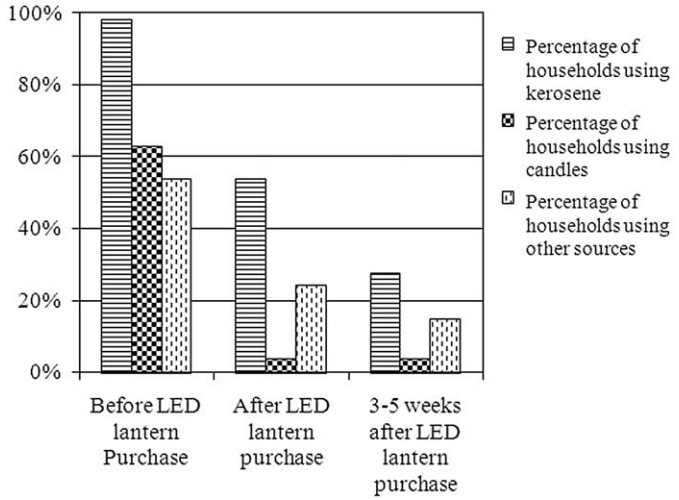

Fig. 3. Percentage of households using light sources apart from LED lantern (n=54).

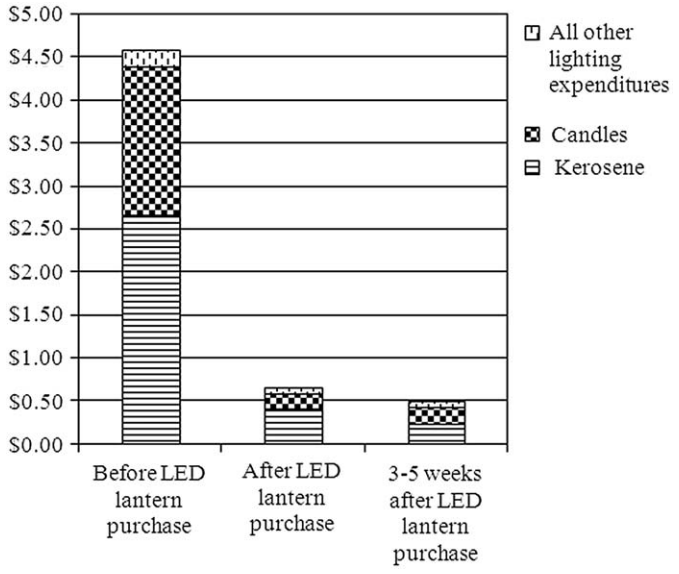

Fig. 4. Monthly recurring household lighting expenditures (US$), excluding price of LED lantern (n=54).

were surveyed three to five weeks later, the proportion of households using fuel-based lighting declined further.

Households reported significantly lower recurring expenditures for lighting after purchasing the LED lantern.[2] On average, buyer households spent $0.61 per week, on kerosene prior to purchasing the lantern, compared to $0.09 per week after LED lantern purchase. Lighting expenditures on all sources excluding the cost of the LED lantern fell from $1.06 per week to $0.15 per week after lantern purchase, a reduction of 85.7%. These figures, converted into monthly values, are reported in Fig. 4.

A comparison of reductions in household lighting expenditures and lantern cost is presented in Fig. 5. Among lantern buyers, the average annual drop in household lighting expenditures, excluding the cost of the lantern, was $47.06 per household, with a median of $36.63. Taking into account these avoided recurring expenditures the majority of customers paying $29.78 for the LED lantern on cash basis had an average "payback period"

[2] A significance level of 0.05 is used throughout this paper.

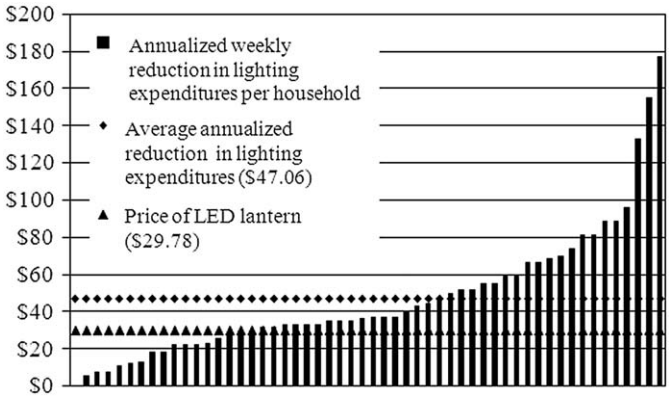

Fig. 5. Reduction in annual lighting expenditures (US$) per household, excluding the price of LED lantern (n=54).

Table 3
Households' reasons for switching to LED lighting for activities using light (n=54, number of responses=142).

Low cost compared to alternatives or lower recurring costs	32.4%
Ease of use or portability or wind resistance	23.9%
Better light	19.0%
Reduced smoke or perceived health benefits	10.6%
Other reason	14.1%

of less than one year. This finding would hold true even at an interest rate of 20%. These benefits are still greater given the expected life of the lantern. Both panels and LEDs are expected to last several years, requiring only battery replacement after about 1.5 years, at a cost of $2.00–$3.00. The magnitude of avoided recurring expenditures did not show a correlation with self-reported household incomes.

Households' changing preferences were reflected in the lighting source they chose for the three most important activities using light. In the week before LED lantern purchase, 147 of 160 responses (91.9%) cited kerosene as the principal lighting source for these activities. In the week after lantern purchase, households switched overwhelmingly to using LED lighting, with 156 of 162 responses (96.2%) citing an LED lantern as the principal source. Households provided qualitative reasons for choosing LED lighting, summarized in Table 3.

Crucially, households reported obtaining significantly greater hours of light from the LED lantern. Households reported using 2.7 h of light per day from kerosene in the week before lantern purchase versus 4.4 h of light per day from the LED lantern in the week after purchase, an increase of 63.0%.

3.5. Information dissemination and payment preferences

Of 54 households that purchased a lantern, 21 (38.9%) reported hearing about or seeing the lantern through a focus group discussion or sensitization meeting, 14 (25.9%) at a vendor's store, 12 (22.2%) through a friend or acquaintance, and 7 (13.0%) through other sources. Thus, while community interactions were important in information dissemination, other sources and word-of-mouth were also critical.

The majority of households paid for the LED lantern in a single cash payment rather than the installment plan. Of 54 households who bought lanterns, 47 (87.0%) purchased on a cash basis and paid $29.78, while 7 households (13.0%) elected to use the installment option, and paid $32.61. Thus, the data suggest that

households or vendors preferred the cash payment plan to installments. Households that used the installment option repaid the cost in 1–3 installments, over 1–3 months. On average, households repaid in 2.1 installments over 1.6 months, for an effective interest rate of ~6% per month.

3.6. Lantern purchasing patterns: buyer and non-buyer households

The survey attempted to estimate the income differences between households that purchased the LED lantern, and those that did not. Such information is fraught with measurement difficulties, especially for the poor, who may not have a single, steady and quantifiable source of income and for whom a single direct question can at best provide only a relative measure of income. Given these caveats, households that purchased a lantern declared a mean monthly cash income of $60.98, with a median of $52.11 ($n$=54) whereas households that did not purchase a lantern reported a mean monthly income of $33.01, with a median of $14.18 ($n$=43). Note that the lantern price falls between these two self-reported monthly income figures.

Given the difficulty of obtaining accurate measures of income among self-employed rural agricultural workers, households were asked a series of "yes/no" questions on their ownership of several easily identifiable proxies for wealth, in a similar procedure to ones used in various surveys in rural areas of other developing countries (see Jalan and Murgai, 2007). These included household items such as a radio, and mobile phone; agricultural assets like crop land and livestock; and the materials of the home, a corrugated iron roof, for example. A simple index was created by coding each "yes" response with a 1 and each "no" response with a 0, and adding all the responses together, with a maximum possible score of 17. Buyer households had a mean wealth index score of 9.0 while non-buyers had a significantly lower score of 6.1, corroborating the differential in self-declared income.

On the other hand, average weekly kerosene expenditures were not statistically different between buyers and non-buyers. The mean weekly expenditure on kerosene among 54 buyer households in the week preceding purchase of the LED lantern was $0.61, with a median of $0.53 per week. Among 43 non-buyer households the mean weekly expenditure on kerosene was $0.59, with a median of $0.43. Distance traveled to purchase kerosene did differ significantly, with respondents from buyer households reporting a mean distance to purchase of 9.4 km, against a mean distance to purchase of 5.0 km reported by non-buyer households.

A greater proportion of buyers, 35 out of 54 (64.8%), reported using candles, against 20 out of 43 non-buyer households (46.5%). The mean weekly expenditure on candles among 54 buyer households in the week preceding purchase of the LED lantern was $0.40, with a median of $0.18 per week. Among 43 non-buyer households the mean weekly expenditure on candles was $0.35, with a median expenditure of $0.00 per week. Average weekly expenditure on candles was not statistically different between buyers and non-buyers.

In summary, it appears that kerosene use is inelastic to reported incomes. For lantern buyers the price of the lantern represented about half a month of reported income whereas for non-buyers the lantern represented two months of reported income. This may suggest that even at a price of $30, and despite critical need, low cost technologies could remain out of reach of the poorest. Microfinance, information dissemination, and the introduction of lower cost models may all enable greater adoption by the poorest.

3.7. Household feedback

Respondents were asked a series of questions about the LED lantern. The questions for those who purchased lanterns were different from the questions for those who did not. Non-buyers were asked, "Have you heard about the rechargeable solar lanterns that have been selling in the villages?" Of the 43 non-buyers surveyed 27 (62.8%) had heard of the LED lantern, while 16 (37.2%) had not. This may indicate that information dissemination efforts as part of the trial were only partially successful. Non-buyers' surveys were administered in the two weeks immediately following completion of approximately two months of buyers' surveys, so timing of the surveys was not likely a key factor, but the spread of information would be expected to occur naturally over time. All 27 households that had heard of the lantern expressed interest in purchasing one, with 23 noting that they planned to do so. Most qualitative responses cited limited financial resources and the high relative cost of the lantern as barriers to buying an LED lantern.

In response to the question whether the LED lantern changed the quality of life for the respondent's family, all 54 households (100%) that purchased an LED lantern responded "yes." Common qualitative responses explaining this answer included reduced expenditures on kerosene and candles, less smoke from kerosene lamps, better light, and the lantern's wind resistance and portability. When buyer households were asked whether they would describe their level of satisfaction with the LED lantern as "high," "medium," or "low," all 54 (100%) households noted that their satisfaction with the LED lantern was "high." Similarly, all buyer respondents would recommend others to purchase one.

In response to the question, "Do you see the lantern providing opportunity for economic development?" 53 of 54 buyer households (98.1%) responded "yes." While the majority of respondents offered no additional explanation, a few (less than 10% of buyers) noted that the lantern had provided expanded business opportunities by allowing more time to work at night. However, the broader question of whether and how the lanterns may provide new opportunities for income generation, extended working hours, and other benefits, would require more detailed study over a longer time period, since labor and income choices involve complex tradeoffs, and household practices may take time to change. As the program passes its one year point, follow-up surveys have begun, targeting households who had owned the lanterns for twelve months or more. Very preliminary results suggest that some households are clearly using the lanterns for income generating activities to a greater extent than they previously used fuel-based lighting. However, precise quantification of income changes will likely be difficult, since responses of lantern users require recall of changing income patterns over long periods during which other aspects of income and daily life patterns change as well.

4. Expansion of sales, capacity building, financing, and scale-up

4.1. Expansion of sales

The initial tranche of 54 LED lanterns sold rapidly, and additional requests to purchase lanterns indicated unfulfilled demand. Successive tranches of lanterns have since sold steadily and quickly, such that up to the time of this writing, approximately 500 lanterns have been sold and demand remains high, with hundreds of individuals expressing interest in purchase. Meanwhile the number of vendors retailing lanterns has increased from three with limited geographic coverage of the Mwandama cluster to ten, with an attendant increase in market penetration.

As sales continued and villagers became more familiar with the products, the project focused on capacity building among vendors and the cooperative to anticipate and prepare for future demand. The goal has been for the cooperative and vendors to assume a greater share of the logistical and financial duties of making bulk purchases and transporting lanterns to the site. Meanwhile partnerships with microfinance institutions, government agencies, NGOs, and private sector partners were to provide financing solutions, expertise, training, and oversight, as well as manufacturing, supply, and logistics solutions.

4.2. Capacity building

In order to strengthen the abilities of the cooperative to act independently, the efforts of the MVP enterprise development staff have focused on business training and engagement with relevant government agencies and microfinance. Initial steps were to write bylaws register the cooperative with the national government, and open its own bank account, all important steps toward functioning legally under the supervision of national regulating bodies with the mandate to oversee and audit the cooperative in the future. Additionally, national certification has allowed the cooperative to begin the process of securing status as a duty-free importer of solar lighting technologies.

4.3. Financing mechanisms

Thus far, installment plans offered by vendors have had limited success, and are particularly unpopular among vendors because buyers that have chosen this payment option often delay payments relative to agreed upon schedules. Nevertheless, the total repayment rate is approximately 80%, while vendors complain of time-consuming efforts needed to collect the remaining 20%. Vendors are also reluctant to sell LED lanterns on installment plans because demand has outstripped the supply of lanterns, allowing preferential sales to households that are able to pay cash in full. Vendors have shown a similar preference for cash payment in their own purchases of lantern supply from the cooperative, generally avoiding purchasing lanterns under the cooperative's installment plan.

A partnership has been established with the Opportunity Bank of Malawi (OIBM), a commercial and microfinance bank, in part to replace the role of the installment plans but also to provide other banking services. OIBM has an established presence in the village cluster, offering small scale agricultural finance services related primarily to agricultural inputs. In addition, large numbers of villagers have been organized into lending groups for lantern purchase. This partnership has resulted in the provision of four key services. First, OIBM provides micro-lending services for LED lantern purchase through group lending, a well-proven technique with high repayment rates (see Cull et al., 2009), allowing the program to extend credit to the very poor without requiring vendors to offer an installment plan. Second, OIBM has the capacity to provide loans for lantern purchase to vendors themselves, particularly as vendors gain more experience with lantern sales and their assets and business skills grow. Third, OIBM will provide larger loans to the cooperative to facilitate bulk purchases of 1000–1500 lanterns, using revenue gained from sales of donated lanterns as collateral. Finally, OIBM can assist international purchases by offering foreign exchange services, letters of credit, and financial transfers.

4.4. Scale up

The next stage of the LED program in Malawi is planned for the second half of 2009 and beyond. The first step is purchase and import of 1000–1500 lanterns, which will then be sold not only within the Mwandama Millennium Villages Project cluster area, where sales have previously been confined, but also to the population outside this area as well as to the village of Gumulira, an MVP site in Central Malawi where the lanterns have been demonstrated and demand has been expressed, but sales have not yet begun.

5. Review of major findings and implications for development practice

5.1. The impact of LED lantern purchase on household lighting patterns

Our principal finding is that LED lanterns induced dramatic changes in lighting patterns for buyer households. The number of households relying on traditional lighting sources decreased after lantern purchase as households reported switching overwhelmingly to using the LED lantern. The reported reductions in weekly fuel expenditures for lighting when annualized were $47.06 average per household, an amount greater than the price of the LED lantern of $29.78. This is comparable to Agoramoorthy and Hsu's (2009) finding that households in western India earning an annual family income of $150–250 avoided annual energy costs of $91.55 on average due to solar photovoltaic lanterns costing $87.50.

This study was not able to quantify a significant increase in the amount of time students spent studying or in household productivity. However, other studies suggest such potential benefits. Agoramoorthy and Hsu (2009) find that the average study hours of students per household rose from 1.47 h to 2.71 h, with a positive effect on school performance, while women were able to perform routine household work during power outages. Johnstone et al. (2009), using self-reported data from Kenya, find that LED lighting had a positive impact on night market business prosperity through reduced kerosene expenditures and increased traffic to shops using LEDs.

5.2. Community participation

Sustained community participation was critical to the trial's development. Early vendor interviews and focus group discussions allowed the team to assess vendors' businesses as well as shop owners' willingness and capacity to sell LED lanterns. Vendors were educated about the benefits of LED lighting and discussed the proposed business models. Similarly, interactions with villagers served as an educational tool about the technical features of the LED lanterns, business models, and processes, such as contracts. Participants were shown comparative figures of kerosene expenditure, and were thus able to compare the cost of kerosene to that of the LED lantern. By cautioning people about the trial nature of the program and technology, the program also endeavored to mitigate possible market spoilage in case flaws in the product emerged over time, since laboratory testing was limited in duration relative to the product's lifespan. Ongoing engagement with the cooperative has provided demand information and other feedback that has guided lantern orders and supported involvement of microfinance partners.

Community interactions also served as a means of simplifying the trial. The community's strong preference for one lantern model allowed elimination of two competing models, greatly streamlining planning, training, purchasing and sales. The negative reaction of focus group participants towards lantern rental similarly led to the elimination of this payment option and the related administrative complexities. Finally, focus group discussions were valuable in choosing vendors that the community perceived as trustworthy and competent.

5.3. Lantern purchasing patterns

The overwhelming majority of households (87%) purchased the lantern in one payment for $29.78 instead of installments for $32.61. Buying patterns may reflect customers' preference for a single payment given the additional cost of installments. However, the high demand for lanterns under group lending programs through the microfinance program offered by OIBM involve a similar increase in total costs to the consumer, so the higher price alone is probably not the primary explanation of the low number of sales through the installment plan. Instead, our tentative conclusion is that vendors who bear the financial risks of default as well as transaction costs of seeking repayment from customers under the installment plan simply preferentially sell to those who can pay in cash, despite larger profit margins from a sale under the installment plan.

Households that purchased the lantern early on declared significantly higher incomes and greater ownership of assets than those that did not. This is in accord with other programs' implementation experience with SHSs (e.g. Acker and Kammen, 1996). Although this may indicate that wealthier households were simply early adopters of this technology, it may be that less wealthy households are unable to purchase LED lanterns at current costs. Feedback from non-buyers supports the conclusion that cost was a determining factor in households' decision to purchase the lantern. Because mean kerosene expenditures for lighting were not statistically different among buyer households and non-buyer households, poorer households may experience a net benefit of lantern ownership, provided difficulties with or resistance to initial purchase can be overcome. Recent progress in microfinance, with hundreds of villagers pledging to pay for LED lantern orders through group lending, has potential to resolve this barrier to adoption.

However, it is not yet clear whether even this route can improve access for the very poorest rural villagers. It may be helpful to consider other approaches such as microfinance options based on schedules of avoided kerosene expenditures, and fee-for-service solutions provided by local micro-entrepreneurs (although this model was initially rejected during community focus group discussions). But given the $30 price for the LED lanterns sold in this trial, the transaction costs involved on such small amounts could be relatively large, perhaps reducing microfinance schemes' attractiveness to profit-driven institutions (see Cull et al., 2009). One novel approach cited by Urmee and Harries (2009) is the use of an interest rate buy-down wherein subsidies are offered to local partner financial institutions which are then able to provide loans at discounted interest rates, reducing distortions in the market for lanterns (UNEP, 2006). Carbon credits based on avoided emissions from fuel-based lighting could also be used to reduce costs (e.g. Sarkar, 2008). Since these reductions are limited in magnitude, a solar LED project would need to be of a large scale to utilize carbon crediting through the Clean Development Mechanism (see Wamukonya, 2007). One option the project is now investigating is to offer lower-priced LED lantern products with lower battery capacity. Finally, subsidies, especially of initial costs, may play a role in reaching the poorest.

5.4. Sustaining the LED lantern program

LED lanterns proved successful at providing superior lighting at equal or lower costs than kerosene fuel-based alternatives in Mwandama, but issues related to the program's long-term sustainability remain. The technical performance of the LED lanterns both in laboratory and field testing has thus far been robust, decreasing concerns over product quality as a hindrance to scale-up. In preliminary surveys of villagers who purchased lanterns in the summer and fall of 2008, most owners report no noticeable decline in lantern performance after roughly one year of nearly daily use. This suggests that problems related to deep discharge, memory affects, and other potential damage from repeated use of sealed lead-acid batteries have been largely prevented by the lanterns' protective circuitry, and that typical temperatures in Southern Malawi are not causing an unusually rapid decline in batteries.

However, long-term use of LED lanterns will eventually require battery replacement. Efforts by Project staff to identify battery suppliers and recyclers in the nearby city of Blantyre have thus far achieved limited success. Procurement of batteries locally will likely be possible, though prices are variable and sometimes prohibitively high, ranging from as little as one-eighth to as high as one-quarter of the lantern's retail cost. Moreover, although recyclers for flooded, vehicle-sized lead-acid batteries do exist in Blantyre, the MVP staff has yet to locate a company that will accept the smaller, sealed lead-acid batteries of the type widely used in portable lanterns. Meanwhile, some lantern manufacturers are working to establish supply chains for lanterns, batteries, replacement parts and fulfillment of warranties in the case of product defects.

Future shipments of solar lanterns will likely be spurred by innovations such as features enabling charging of mobile phones and power supply to portable radios, which are already appearing in new products and have been met by strong consumer demand.

Efforts have been made to ensure the sustainability of the cooperative's and vendors' business by including markups to provide incentives and incomes to support future activities, establishing substantial "working capital" in the cooperative through an in-kind donation of lanterns with a value of approximately $25,000, and by forming well-established links to a microfinance organization for financing solutions. Consequently, the financial and institutional capacity of the cooperative has grown in magnitude, geographic extent, and range of services, all of which suggest good potential for sustainability.

The contribution of the Government of Malawi toward sustainability of the lantern program has been important in two fundamental ways. First, as the village lantern cooperative became established, the Ministry of Trade and Industry provided direct support in the form of training and assistance with writing of bylaws and registration. Now registered, the cooperative operates under the Ministry's authority, which includes supervision and occasional additional training. The government of Malawi also supports the lantern program indirectly through tax policy, including granting duty free import status for solar lanterns, as well as allowing VAT exemption for sales of lanterns by the cooperative, provided it registers itself and the products it sells with the Malawi Energy Regulatory Authority.

Nevertheless, key sources of future uncertainty remain. One question is whether cooperative and vendors will thrive in the medium-to-long term, once initial lantern sales have saturated the local market. Modern energy sources can contribute to increasing household productivity and incomes (Modi et al., 2006; Saghir, 2005), and engender broader and deeper markets for such products. Accordingly, the expansion of sales beyond the geographic borders of the Project area is being encouraged, while efforts are also underway to expand the cooperative's activities to include the sale of other related products, starting with energy efficient cook stoves. However, the testing and introduction of such products is often expensive, time consuming, and knowledge-intensive. Finally, participation of vendors and the cooperative in microfinance schemes will allow them to reach new customers, but the cost of borrowing could lower profit margins

and reduce incentive to sell lanterns, particularly among remote, highly dispersed rural populations and the very poorest.

While the long-term success of the trial remains to be seen, its design is largely in agreement with the components of a successful program Urmee and Harries (2009) identify in surveying solar photovoltaic program implementers. It includes an appropriate financing mechanism with regular revenue collection, systems that are easy to operate and based on users' needs, rigorous monitoring and evaluation, strong community involvement, creation of local income generation opportunities, government participation, and a capacity building component. Provision of spare parts, maintenance, and warranty services through a supply chain established by the manufacturer may complete the list of elements that these authors identify as keys to an enduring lantern sales program.

6. Conclusion

Sales and survey data indicate that the Millennium Villages Project lantern trial in Malawi succeeded in its primary objective of introducing LED lanterns that provided households with brighter lighting for a longer duration at equal or lower cost over time than fuel-based alternatives. Despite questions related to supply chains for lantern products and viability of local cooperatives, similar market based models of LED lighting technology dissemination have the potential to be replicated and scaled up in other off-grid regions across the developing world.

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Appendix A. Lantern models

See Table A1.

Appendix B. Households' decision to buy

In order to better understand households' decision to purchase the lantern, regressions were performed to assess statistical correlations between characteristics of households and their decision to purchase the lantern. We use data on 54 buyer households and 27 non-buyer households that had heard of the lantern, for a total of 81 households.

Households' decision to purchase an LED lantern or not is investigated in the following probit model, which treats household's decision to purchase a lantern as a nonlinear function of several factors. By construction, the model confines the predicted probabilities to a range between 0 and 1.

$$P(y=1|x)=G(\text{Income},\ \text{Wealth},\ \text{Kerosene expenditure},\ \text{Candle expenditure},\ \text{Family size},\ \text{Male education},\ \text{Female education},\ \text{Kerosene purchase burden}) \quad (1)$$

In Eq. (1), the dependent variable, Lantern Purchase, takes the value of 1.0 for households that purchased an LED lantern and 0 for those who did not.

Given the relatively high cost of the LED lantern, the variables Income and Wealth are hypothesized to be positively associated with lantern purchase. Income refers to self-declared average monthly cash income (US$). The variable measuring household wealth, Wealth, is derived from household's scores on a wealth index calculated from their ownership of 17 asset indicators.

Households with higher expenditures on kerosene and candles were expected to achieve greater reductions in recurring fuel expenditures by purchasing an LED lantern. Thus, the variables measuring weekly recurring expenditures (in US$) on fuel for lighting, Kerosene expenditure and Candle expenditure, have an expected positive sign.

Family size, measuring the number of family members in a household, has an expected positive sign as larger families were hypothesized to be able to secure more utility by sharing improved lighting from the LED lantern, or by putting it to more numerous uses. Additionally, family size in the sample is closely related to the number of children in a household, so that households would presumably obtain better light for studying children, one of the benefits reported by implementers of solar photovoltaic programs (Urmee, Harries, 2009; Agoramoorthy, Hsu, 2009).

Male education and Female education measure the number of years of education that the male and female head of household had. We hypothesize that higher levels of education would predispose individuals towards faster adoption of new LED technologies in accordance with results reviewed by Feder et al. (1985) that suggest that farmers in developing countries with better education are early adopters of modern technologies. Thus both variables enter the model with a positive sign.

Table A1
Basic technical features of three selected lantern models (letters are used in place of brand names).

Model	Base cost (bulk price+ shipping cost) in US$	Charger	Light settings	Estimated battery life on full charge and high setting in hours
A	$27.3	Sold with a solar panel enabling charging at home	High, medium, low, very low	10–15
B	$24.8	Sold with a solar panel enabling charging at home	High, medium, low	5
C	$34.7	Recharged at a shop either using a plug-in wall adapter or a solar panel intended to recharge 5 lamps	High, low	15

Kerosene purchase burden is measured by the average distance (km) households traveled to purchase kerosene. Higher purchase burdens, indicated by longer distance to purchase, are hypothesized to have a positive correlation with LED lantern purchase.

Basic descriptive statistics are presented in Table B1. Regressions on the decision to purchase the lantern are presented in Table B2. Data are missing for two sets of variables: Male and Female education, because some households had a female head, and Kerosene purchase distance, because the question was formulated after some households had already been surveyed. Rather than discard information by using only one model, three models are used. Model (1) excludes Male education and Female education and Kerosene purchase distance, and has a sample size of 81. Model (2) includes Male education and Female education and has a sample size of 68. Model (3) includes Male education and Female education as well as Kerosene purchase distance and has a sample size of 45.

See Tables B1 and B2.

Income and Wealth, as expected, are positively correlated with households' decision to purchase a lantern, and are significant at the 0.05 and 0.01 levels, respectively, in model (1). In model (2) and (3), Wealth remains a significant predictor of Lantern Purchase at the 0.01 and 0.05 levels. However, Income is significant only at the 0.1 level in model (2), and is not a significant predictor in model (3), although the sign remains positive. Thus, other things equal, the data suggest that wealthier households were more likely to purchase an LED lantern.

On the other hand, Kerosene expenditure is unexpectedly negatively correlated with Lantern Purchase, although the

Table B1
Basic descriptive statistics.

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Descriptive statistics: all households					
Lantern purchase	81	0.67	0.47	0	1
Income (US$)	81	48.91	48.80	3.54	283.59
Wealth	81	8.02	2.22	3	13
Kerosene expenditure (US$)	81	0.63	0.47	0	2.55
Candle expenditure (US$)	81	0.40	0.60	0	3.83
Family size	81	4.67	2.04	1	12
Male education	70	8.56	3.65	0	16
Female education	79	5.87	3.19	0	12
Kerosene purchase burden (km)	53	6.38	5.77	0.2	24
Descriptive statistics: buyer households					
Lantern purchase	54	1	0	1	1
Income (US$)	54	60.98	53.25	3.54	283.59
Wealth	54	9.02	1.72	5	13
Kerosene expenditure (US$)	54	0.62	0.46	0	2.55
Candle expenditure (US$)	54	0.40	0.61	0	3.83
Family size	54	4.85	2.15	1	12
Male education	49	9.10	3.66	0	16
Female education	53	6.04	3.39	0	12
Kerosene purchase distance (km)	26	9.33	5.97	0.5	24
Descriptive statistics: non-buyer households					
Lantern purchase	27	0	0	0	0
Income (US$)	27	24.79	25.28	3.54	106.35
Wealth	27	6.04	1.72	3	9
Kerosene expenditure (US$)	27	0.67	0.51	0.21	2.48
Candle expenditure (US$)	27	0.40	0.58	0	1.99
Family size	27	4.30	1.79	2	9
Male education	21	7.29	3.38	2	12
Female education	26	5.54	2.77	0	10
Kerosene purchase burden (km)	27	3.53	3.89	0.2	14

Table B2
Regressions for lantern purchase (standard errors in parentheses).

Independent variable	**(1)**	**(2)**	**(3)**
Constant	−4.354*** (1.078)	−4.262*** (1.409)	−5.006*** (1.664)
Income	0.00014** (0.000066)	0.00012* (0.000067)	0.000086 (0.000087)
Wealth	0.617*** (0.148)	0.548*** (0.158)	0.491** (0.202)
Kerosene expenditure	−0.0032 (0.0032)	−0.0024 (0.0032)	−0.0047 (0.0045)
Candle expenditure	−0.0091** (0.0042)	−0.0088** (0.0043)	−0.0080 (0.0054)
Family size	0.042 (0.115)	0.129 (0.157)	0.175 (0.201)
Male education		0.068 (0.083)	−0.011 (0.099)
Female education		−0.073 (0.095)	−0.053 (0.141)
Kerosene purchase burden			0.143** (0.071)
PseudoR^2	0.50	0.45	0.53
Number of observations	81	68	45

* Significant at the 0.1 level.
** Significant at the 0.05 level.
*** Significant at the 0.01 level.

coefficient is not significant in any of the models. Similarly, Candle expenditure has a significant negative correlation with lantern purchase at the 0.05 level in model (1) and (2), but its coefficient is not significant in model (3). A possible explanation for this puzzling finding could be that households with higher spending on candles were accustomed to using this source and were thus unwilling to switch to LED lighting.

Family size, Male education, and Female education are not significantly correlated with Lantern Purchase. Kerosene purchase burden, measured by the distance to purchase, is positively correlated with lantern purchase at the 0.05 level, suggesting that households that traveled greater distances to purchase kerosene were more likely to purchase an LED lantern.

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