Designing affordable solar lighting: Energy-efficient LED design reduces payback to 5 months for Zambian customers

By

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B.A. (University of California, Santa Barbara) 1999

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Community Development

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

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2012

Designing affordable solar lighting: energy-efficient LED design reduces payback to 5 months for Zambian customers

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May 2012

Abstract

The economic, health, and environmental costs of kerosene, candles, and other fuel-based lighting are well-documented. As a result of efforts by the World Bank and other organizations, a new category of solar-powered lighting, the solar portable light, is being promoted as a more affordable alternative to fuel-based lighting. This paper uses the UC Davis Lighting the Way Zambia project as a case study to understand the minimum manufacturing costs of an affordable solar portable light. The study examines functional preferences of users in Zambia, translates these into performance requirements, and then determines the cost implications for those requirements. The results suggest that an 18-lumen solar portable light with a 4-hour run time would meet many users' needs, and could be manufactured for approximately US$9 per unit and sold for approximately US$18-$20 retail (about half the industry average), resulting in a payback period of about 5 months. While no definitive threshold has been established for affordability in this product category, users in Zambia indicated that a payback period of 2-3 months would result in much higher rates of adoption. The paper concludes with some discussion of ways in which manufacturing costs could be reduced, although there is currently no clear design configuration that would achieve a 2-3 month payback for customers in Zambia.

[1] More details on this project freely available at the UC Davis Program for International Energy Technologies website, http://piet.ucdavis.edu.

Contents

Introduction

An estimated 1.5 billion people (including 74% of the population of sub-Saharan Africa) do not have access to electricity, and must rely on fuel-based lighting—kerosene, candles, wood, and other biomass (UNDP 2009). Fuel-based lighting carries high costs for end-users worldwide, including: *economic costs* – $38 billion a year, or an average of $77/year per household; *health/safety costs* – thousands suffer from indirect effects of combustion including smoke inhalation, house fires, and burns; and *environmental costs* – burning of lighting fuels releases an estimated 190 million metric tons CO_2 equivalent (Mills 2005). The most common fuel worldwide, kerosene, is an inefficient source of energy for illumination, such that lower-income households not only pay significant amounts for the kerosene that they use, but the lighting "service" they receive—defined as the amount and quality of illumination—is significantly lower as compared to electrified households or even propane lanterns. For example, users of basic kerosene lamps pay 150 times more per useful unit of lighting than users of grid-connected compact fluorescents (Mills and Jacobson 2008). In Africa, population growth is expected to outstrip growth of the electrical grid infrastructure, meaning that the current unelectrified population of 110 million households is projected to increase to 120 million households by 2015 (LADM 2010). The mounting pressures of population growth and environmental sustainability make fuel-based lighting an important issue to address.

The increased attention on the off-grid lighting industry has resulted in new research over the last 10 years, ranging from performance analysis of kerosene lamps to qualitative studies of health impacts, but little research has been published that connects user preferences and functional performance with actual product component costs. Although some of the organizations developing SPLs are nonprofit or university-based, many are for-profit entities, and almost all those contacted by the author were reluctant to share information on their product designs, manufacturing costs, and operations (including pricing). This reluctance is somewhat surprising, given that the technology used in virtually all SHS and SPL systems is standard, off-the-shelf circuitry and components.

This research addresses this gap in the literature using a specific project in Zambia as a case study. The research sought to 1) understand Zambian users' needs and preferences around off-grid lighting, 2) develop functional requirements based on those needs/preferences, and 3) connect those functional requirements to actual product component costs. The results indicated that a solar-powered light that offers at least 15 lumens of illumination, for 4 hours per night, with a replaceable battery, may be acceptable to candle and kerosene users in Zambia. By focusing on an energy efficient LED, a light that met these performance requirements was manufactured at a cost $8.86 per unit, which would result in a retail price of approximately $20. Given the small (<5,000) volume of the initial manufacturing, the assembly costs and passive electronic components were the largest components of the product cost, meaning that higher-volume runs would see significant cost decreases.

The paper begins with a brief overview of solar photovoltaic technology, and its history as an alternative power source for lighting in the developing world. This is followed by background of the project and Zambian demographics. The methodology section is separated into two categories: methods for understanding user preferences, and methods for understanding product component costs. This is followed by a results section, and then a description of the final product design and cost analysis.

Project background

Solar technology as an alternative

For sub-Saharan Africa and other regions that receive substantial solar radiation year-round, off-grid lighting systems that use solar photovoltaic (PV) technology are considered a promising alternative to fuel-based lighting. Solar-powered lights can be used anywhere there is sunlight, they charge with use of the solar panel during daylight hours, and their operation creates no soot, emissions, or direct fire risks. For these reasons solar PV technology has been widely promoted as a cost-effective means to provide lighting services for rural areas where it is too expensive to extend the electricity grid.

The longer-term interest in solar PV systems has accelerated in recent years, as concerns over greenhouse gas emissions have increased the promotion of solar technology as a clean, renewable resource, especially when it replaces the use of fossil fuels such as kerosene (Wamukonya 2005). It is important to note, however, that benefits of solar PV systems are valued differently among stakeholders. End-users are most interested in the financial savings and performance improvements over fuel-based lighting, and it is typically only international NGOs, regulators, or private sector investors that place direct value on the aggregate environmental benefits. (Wamukonya 2005).

Solar home systems

The most widely promoted category of solar technology for off-grid lighting use is the solar home system (SHS). SHSs have been used for decades, with millions of systems distributed in developing countries (Nieuwenhout, van Dijk et al. 2000). SHSs typically range from 20-100 watts, and at the higher power levels can support other devices in addition to lights, such as TVs, radios, or mobile phone chargers. SHSs typically comprise one or more solar PV panels, a charge controller, a battery, and DC-compatible fluorescent light bulbs.

Proponents of SHSs promote the cost-effectiveness of these systems, often using “levelized cost” or “total cost of ownership” to show that the full lifetime costs of the system per energy service provided are low, due to the essentially negligible operating costs. However, despite widespread funding and subsidies from international development agencies, NGOs, and local governments, market penetration of SHSs has been limited. Primary barriers to adoption include the high initial investment cost (typically $200-$600 retail price) and the technical expertise needed for professional installation and maintenance (Nieuwenhout, van Dijk et al. 2000; Peon, Doluweera et al. 2005; Wamukonya 2005). The high initial investment cost requires financing, subsidies, donations, or some combination of these, thereby limiting adoption of these systems. The one partial exception is in Bangladesh, where a subsidized SHS program that relies on the country’s extensive micro-finance network to finance, sell, and install systems, has sold 645,033 systems as of August 2010 (IDCOL 2010). But in regions and communities where appropriate credit mechanisms are not readily available, SHSs are less accessible.

Solar portable lights

A growing number of smaller off-grid lighting products, sometimes referred to as “solar lanterns, “micro” or “pico” solar lights, are currently entering the market. The author follows the recent convention of the Lighting Africa Development Marketplace and refers to this category as “solar portable lights” or SPLs (LADM 2010). These systems typically use less than 10 watts of power, cost $20-$70, and are self-contained products that emulate lanterns, torches (flashlights), or desk lamps in size and form factor. Compared to SHSs, solar portable lights are generally less robust, with lower service capacity, lower efficiencies, and shorter product life spans. However, the lower retail price of solar portable lights, around 10% of a SHS, makes them more accessible to a broader segment of unelectrified households. Therefore while less cost-efficient compared to the larger SHS or community-scale solar systems, solar portable lights can still offer significant cost, performance, and health benefits to the end user switching from fuel-based lighting. Table 1 provides a basic comparison between the costs and features of SHSs and SPLs.

Table 1: Comparison of SHS and solar portable lights[2]

System	Typical upfront cost (USD)	Lighting service	Other services?	Typical product warranty	Requires technical installation	Requires maintenance
Solar home system	$200-$600	450-3600 lumens	Potentially	3-20 years	Yes	Yes
Solar portable light	$20-$80	10-70 lumens	No	0-1 year	No	No

Demand for lighting that is more affordable than that provided by SHSs is reflected in positive customer reactions to SPL product testing with kerosene users in sub-Saharan Africa (Mills 2007; Radecsky,

[2] SHS estimates are based on data from a major SHS manufacturer in Bangladesh. The warranties offered for these SHSs are: 3 years for charge controller, 5 years for battery, and 20 years for solar PV. SPL estimates based on LADM (2010) market report, manufacturer warranties, and anecdotal evidence.

Johnstone et al. 2008; LADM 2009) and, more tellingly, in growing global sales figures for those organizations with established SPL products and distribution (Friedman 2010; LADM 2010). However, even at a cost of $20-$70 per SPL, many poor still cannot pay full retail price without some type of financing. So despite having an upfront cost that is an order of magnitude lower than a SHS, solar portable lights that require financing face a significant barrier to widespread adoption among many low-income households. There is therefore movement among companies that develop and distribute SPLs toward designing even lower-cost models in the $5-$20 range: the World Bank reports that at least a dozen of its accredited SPL manufacturers plan on introducing lower-cost products (LADM 2010). Some of the leaders in the SPL industry who are developing lower-cost SPL models include d.Light, Cosmos Ignite, and Barefoot Power.

In summary, the off-grid solar-powered lighting industry appears to be following a general trend toward increasingly lower-cost lighting alternatives to kerosene, moving from solar home systems, to solar portable lights, to ultra-affordable solar portable lights. This trend is likely driven in part by movement away from philanthropic or heavily subsidized distribution in favor of market-based distribution models, as well as by steadily decreasing component costs for solar PV, LEDs, and other electronics, which enables lower manufacturing costs for equal or superior product performance.

Lighting the Way Zambia

Partly as a response to the growing demand for solar portable lights, the World Bank launched its Lighting Africa Development Marketplace (“LADM”) program in 2008 to help spur innovation and growth in the solar portable light industry (LADM 2008). The UC Davis “Lighting the Way Zambia” team was one of 16 organizations that received funding from LADM to design, build, and distribute an affordable solar portable light to compete with fuel-based lighting. The UC Davis team selected Zambia as its focus country due to principal investigator (PI) Kurt Kornbluth having an established relationship with a local NGO, Disacare, with whom he had worked with previously.

Given that the relatively high upfront cost of most SPLs puts them out of reach of lower-income households, the UC Davis proposal to the World Bank committed to developing a solar portable light that could be purchased by kerosene and candle users *without subsidy or financing*. The design process was therefore framed by the focus on an affordable retail cost, and understanding whether it was possible to meet users' minimum functional, aesthetic, and performance requirements within that cost structure. It is worth noting that the World Bank LADM funded a variety of different business models (e.g., rental instead of purchase of lights) and product designs (e.g., using a hand-powered charging mechanism instead of solar PV).

As part of the project grant, the UC Davis team worked with Disacare to establish a Zambian business to distribute the lights. Disacare provided administrative oversight and operational support, including transportation, office space rental, accounting services, legal services, and other administrative support. The business "Lighting the Way Zambia" was registered with local authorities, and the author hired and trained two staff members on contract. The two staff members helped UC Davis team members conduct research while in Zambia, and also conducted ongoing market research on their own. However, the staff members were hired primarily as sales and marketing managers to distribute the product once it was manufactured. Due to unexpectedly lengthy delays with the manufacturing process, the staff members' contracts were eventually allowed to lapse as there was no product for them to sell, and no more funding to pay their salaries. In October 2011, six months after their contracts ended, the first pilot run of the product was ready to be shipped.

The UC Davis team was led by PI Kurt Kornbluth and the author, with other graduate students providing specific research tasks or support functions. The author served as project manager, with responsibilities that included market research and analysis, product development, business development and training in Zambia, subcontractor management, and reporting.

Country background: Zambia

Zambia has a population of almost 12 million, more than half of which live in rural areas. While an estimated 18% of the total population has access to grid electricity, only 2% of those living in rural areas have grid access (LADM 2009). Therefore, a core target customer segment was the rural communities that have little chance of ever having electricity extended to their area. Another customer segment was represented by households living in peri-urban communities, on the outskirts of the urban core. These communities, called "compounds" in Zambia, are often unplanned or informal settlements, and while geographically close to the city center, are generally excluded from city services such as water, sewer, and electricity. This research focused on these two customer segments as potential end-users, and therefore sought to understand their preferences and cost constraints.

Recent research commission by the World Bank (LADM 2009) showed average income levels in Zambia of approximately US$150 per month, with urban incomes typically slightly higher than rural incomes. As a landlocked country with generally poor infrastructure, the cost of goods in Zambia is relatively high, especially in rural areas. The World Bank study reported average expenditure on off-grid lighting to be in the range of $3.50 - $4.75 per month. Somewhat unique to Zambia is a much higher incidence of candle usage vs. kerosene, or paraffin. The World Bank study showed a majority of unelectrified households across Zambia use candles (79%) instead of kerosene (14%). This contrasts sharply with Kenya, which is more representative of sub-Saharan African countries in general, where 5% of households use candles and 67% use kerosene (LADM 2009; LADM 2009). The UC Davis team sought to validate this key difference in Zambia, and explore any effects this preference for candles might have on acceptance of alternatives.

Previous research

The two most comprehensive sources of research specifically on fuel-based lighting and the SPL market are the World Bank and the Lumina Project, both of which publish non-peer-reviewed reports. The World Bank has sponsored the Lighting Africa Development Marketplace program (see *Project Background*), which commissioned extensive market research in five countries in sub-Saharan Africa that is available free on its website. These studies are country-specific market analyses that include very detailed demographic and lighting usage/behavior information. The Lumina Project, from Lawrence Berkeley National Laboratory, produces both field and laboratory studies that it makes freely available; the latter includes photometric testing of kerosene lanterns and LEDs (including recommended test procedures and metrics), while the former includes studies in Kenya and other countries evaluating household usage of kerosene and reactions to SPLs.

The majority of academic peer-reviewed articles are older and focus on SHSs (Nieuwenhout, van Dijk et al. 2000; Wamukonya 2005), with the exception of two articles recently published specifically on SPLs, or "solar lanterns" (Velayudhan 2003; Adkins, Eapen et al. 2010). However, very few reports, and no peer-reviewed academic articles, were found that had detailed product performance criteria linked to cost information. Possible reasons for this are that researchers believe that prices change too quickly for this research to be relevant, or that researchers are not involved with commercialization aspects of such projects.

Research methodology

The research conducted can be grouped into two categories: that aimed at understanding user preferences, and that exploring how functional requirements translate into actual manufacturing costs. Although the UC Davis project was focused on the Zambian market and its users, the latter category of research on development and production costs should be relevant for products sold in other markets outside Zambia. It is worth noting, however, that factors such as transportation infrastructure, governmental regulation, and import tariffs/taxes can all have significant effects on final retail prices.

Understanding user preferences

The team used both primary and secondary data to inform its understanding of user preferences around lighting, including current lighting usage habits, lighting expenditures, and general preferences toward form and functionality. The secondary data included comprehensive, country-specific quantitative and qualitative research studies conducted and published by the World Bank LADM prior to, and during, the project period (LADM 2009; LADM 2009). Other reports used included several from the Lumina Project (Mills 2003; Radecsky, Johnstone et al. 2008; Jacobson 2009). While the field research done by the Lumina Project team took place in Kenya, some of the results were deemed relevant and applicable to the Zambian market. For example, the Lumina team conducted field trials with micro-businesses to evaluate user preferences to different levels of illumination for their business, measuring actual lux output on the display of products at different kinds of micro-businesses, such as produce vendors (Radecsky, Johnstone et al. 2008).

The UC Davis project team, led by the author and project PI Kurt Kornbluth, and Zambian staff conducted primary research to validate and extend the data in published reports. Over the course of two trips to Zambia (approximately 7 weeks total), the team conducted research with kerosene and candle users to learn about current lighting behavior, perceptions of existing lighting, and lighting expenditures, both in terms of initial investment costs and ongoing operating expenses.[3] Methods included focus groups, one-on-one interviews, and in-person surveys. The research was conducted in rural and peri-urban communities around Lusaka. Rural communities included Kanakantapa, Kafue, Chilanga, and Chongwe; peri-urban communities of Lusaka included Chunga, George, Desai, Chawama, Kanyama, and Kalikiliki.

Because one of the goals of the project was the establishment of a financially and technically sustainable business in Zambia, efforts were made to train the Zambian staff to conduct objective market research. However, the staff had been hired based on their marketing and sales skills, not research capabilities, and

[3] The team also spent time considerable time researching distribution channels, marketing opportunities, and potential retailers to inform future marketing and operational strategies, but this lies outside the scope of this paper.

the training provided by the author was rudimentary at best. As a result, the method of engagement, degree of scientific rigor, and objectivity of analysis varied widely based on who was leading the research. See the section *Limitations* for more on this topic.

For the focus groups, one of the Zambian staff would contact a community leader with which he had an existing relationship. Requirements for communities were that they were geographically close enough to Lusaka such that visits could be conducted in one day. The community had to be either completely off-grid (rural or peri-urban), or connected to the grid but with majority of residents without connections (peri-urban). The community leader was instructed to assemble a group of community members who met two requirements: being a full-time resident of the community, and being a user of candles or kerosene for lighting. The focus groups were scheduled for the evening in order to provide the most realistic context for demonstrating the relative illumination of candles, kerosene lamps, and prototype SPLs. Typical group size ranged from 4 to 12 people. A standard script with a set of questions was usually followed, though this varied depending on the researcher conducting the focus group. The questions were also refined over time in reaction to responses given. However, the key information being sought stayed constant: current lighting products (e.g., candles or kerosene), current lighting behavior (e.g., how many lit at once, which rooms lit), current lighting expenditures (e.g., both up-front and operating), and reactions to a demo of the prototype. After the focus group, and sometimes before, there were often informal interviews conducted with other community members who were either not invited or not interested in participating in the actual focus group itself.

Surveys were conducted by both UC Davis and Zambian team members in two ways: by assembling a large group of community members and passing out paper surveys to be filled out by the respondents, and by going door-to-door with a clipboard and asking residents to answer similar questions, with the answers recorded by the researcher. While the exact questions varied, they were very similar to the questions used in the focus groups concerning existing lighting behavior and costs (see *Appendix A* for the list of questions).

The UC Davis team conducted six focus groups and approximately 45 interviews (of these, the author conducted four focus groups and approximately 20 interviews), and conducted a single survey of 50 respondents. After the two trips by UC Davis, the Zambian staff continued the research using the same methods. The Zambian team conducted interviews with 122 respondents, and 2 focus groups with 45 respondents.

Table 2. Location of research efforts by Zambian team

Village/Community	# respondents	Method
Kafue	25	interview
15 miles	30	interview
Chilanga	20	interview
Chisamba/Chibombo	15	interview
Lilanda	16	interview
Mandevu	30	focus group
Chongwe	15	focus group
Kalingalinga	16	interview

Understanding manufacturing costs

The other category of research, exploring costs of production for a solar portable light, was conducted primarily by the author. This research was intended to provide a baseline set of product component costs that were considered to provide the minimum SPL performance acceptable to kerosene and candle users in Zambia. Matching component costs with SPL performance attributes was also intended to provide other practitioners with rudimentary guidance on cost-performance tradeoffs in product design. This was accomplished by plugging cost estimates into an optimization calculation to determine a cost-optimized configuration for an SPL that met the specified performance requirements.

The author used published data on kerosene lamp performance (Mills 2003) to assess baseline performance in terms of illumination, measured in luminous flux, or lumens. This key metric was then used as a reference point in the optimization calculation, and the other system component performance was based on achieving this lumen output. The general circuit design was adapted from a published design on an integrated circuit (IC) manufacturer's datasheet (Zetek 2007). This particular IC was designed specifically as a low-power LED driver, so the circuit needed only minor modification. Given the circuit and IC performance, the project team then used a simple optimization calculation and retail prices of key components to select the configuration that met the performance requirements for the lowest cost.

Significant effort was made to determine component and manufacturing costs that would be generalizable production prices for manufacturing the product in mainland China. Component prices used in this calculation were based on retail prices for low (<10,000 pieces) quantities. For the solar PV cell, battery, and cabling, the project team used quotes from Chinese suppliers found through Alibaba.com, a China-based company providing listings, purchasing, and other online business services to importers and exporters around the world. For the LED, the team contacted that LED manufacturer's East Asia distributor for pricing. The less expensive and less significant (e.g., passive) components were priced from one of the largest North American electronics distributors, Digikey, for convenience and very specific pricing—it can be very difficult to get a Chinese OEM manufacturer to provide a detailed cost breakdown for different sized resistors or transistors; typically these are so cheap that they are bundled together with other passive components. For PCB fabrication and assembly, general assembly, packaging, quality assurance, and other costs, the team used actual costs from an OEM manufacturing partner in Shenzhen, China.

Results

In general, the field research conducted in Zambia supported existing data (e.g., from LADM and Lumina) around user behavior and preferences around off-grid lighting. Translating these preferences into performance requirements invariably included some subjective judgment calls; one way in which the team attempted to mitigate this bias was to use a rule of always choosing the least costly option that would still satisfy basic performance. For example, many respondents suggested that an SPL should have a more robust switch, possibly with multiple “modes,” but the project team determined that the most basic on-off switch could still offer the needed functionality.

User preferences

The basic profile of the off-grid household that emerges from the author’s research can be characterized by the following:

- 4-5 people live in the home
- Most households use either candles exclusively, or both candles and kerosene; very few use kerosene exclusively
- Usually 2 or more rooms are lit simultaneously for at least part of the night
- Lighting is used for 3-5 hours per night
- Candle costs range from $0.10 each (smallest) to $0.25 each (largest, high-quality)
- Candles last 1-2 nights, depending on size and quality
- Monthly expenditures on lighting range from $4-$8
- Monthly household income is less than $150
- Candles/Kerosene are purchased multiple times a week in small quantities, from small shops within the community, by any member of the household

The results around user preferences were similar, in most cases, to previously published data on off-grid lighting users reported by the World Bank (LADM 2009). For example, results for hours of lighting per night, household income, types of lighting, and monthly expenditures were very similar. Some differences indicated that the LADM research was conducted in more rural areas (e.g., higher prevalence of grass thatch roofs vs. corrugated iron; slightly lower household incomes).

The question of why Zambians overwhelmingly prefer candles over kerosene, or paraffin, is perplexing and could not be answered completely satisfactorily. Most people in interviews stated their preference for candles was because they burn cleaner, with less soot and fumes, and from casual observation, this seems to be the case. However, candles are slightly more expensive (especially high-quality candles, which last longer) than kerosene. A brief investigation into historical government subsidies, distribution issues, or national-scale shortages did not reveal any events or patterns that might account for the prevalence of candles. While it is perfectly reasonable to believe users' stated preference for candles, the fact that surrounding countries all have an equally strong prevalence of using kerosene for lighting casts some doubt on it being simply a matter of user taste.

The results suggested an interesting difference in gender roles for who purchases candles/kerosene vs. who would purchase a solar-powered light. Respondents indicated that current purchase behavior is relatively equally shared by the man of the household, the woman of the household, and the children. But when asked about purchasing a solar-powered light, the response was strongly skewed toward the man of the household. It is unclear whether this is because of the higher cost of a solar-powered light, because it is a higher-tech product, or because of some other reason. Other countries show a much stronger tendency for the woman of the household to manage the energy budget, including purchasing lighting fuel (LADM 2009), and some practitioners have thus advocated for marketing solar-powered lighting products to the woman. However these results raise some doubts about the validity of this approach in Zambia.

In addition to the typical user preference information around lighting, the project team also asked questions regarding mobile phones in order to better understand user behavior, attitudes, and expenditures for what is for many households their single largest technology investment. This was considered relevant because mobile phones have both a significant upfront cost and an ongoing operational cost (charging), yet have achieved very high penetration rates. Many solar-powered lights are now being produced that can charge mobile phones directly, offering users both lighting and charging functionality. Many in the field, including the author, believe that this synergy will be a fundamental driver of SPL growth—in fact, demand for mobile charging may be much more important than demand for clean lighting.

The table below shows data from the largest single survey that was conducted; other surveys and interviews had similar results. Note that much of the survey and interview data collected in Zambia was lost when the head Zambian staff member, Yuda Tembo, left the organization. Mr. Tembo left the organization on bad terms, and felt entitled to take with him the project laptop, camera, and paperwork.[4]

[4] Mr. Tembo felt that he was owed additional compensation beyond what was in his contract. The issue started with an accounting oversight on the part of Disacare, whereby taxes that were taken out of Mr. Tembo's salary and meant to be paid to the Zambia Revenue Authority (ZRA) had not been paid to the ZRA. Mr. Tembo's response was to suggest that those funds be instead given to him. When Disacare declined and insisted on correcting the error by paying those funds (and a late penalty) to the ZRA, Mr. Tembo threatened legal action. Disacare worked with a Zambian lawyer to ensure that they were complying with all aspects of Zambian contract law and refused to meet Mr. Tembo's demands. When Mr. Tembo left with the project equipment and documents, Disacare reported the theft to the police. Unfortunately, the police have requested ongoing payments from Disacare to fund their investigation and possible collection of the stolen equipment. The incident has served as a potent reminder of the challenges and high costs of doing business in Zambia.

Table 3. Results from largest survey, N=50, conducted by the author in Kanakantapa, Zambia[5]

Type of light used	Candles only	Kerosene only	Both	
	22	1	27	
People in the home	1-2	3-4	5-6+	
	4	21	25	
Number of lights used simultaneously	1	2	3+	
	8	23	18	
Person who purchases lighting	Man only	Woman only	Either	
	19	15	16	
Frequency of purchase	Daily	Weekly		
	30	20		
Distance from home purchased, in km	0-5	6-10	10+	
	47	0	3	
Monthly expenditure on lighting, in Kwacha[6]	5k-20k	21k -30k	31k-40k	41k +
	7	21	15	6
Activities conducted using light	Visiting	Homework	Cooking	Business
	11	35	48	19
Whether children light candle/kerosene themselves	Yes	No		
	29	21		
Hours of lighting used per night	1-2	3-5	6+	
	4	39	6	
Type of roof	Asbestos	Grass	Iron sheets	
	9	0	40	
Level of education of respondent	Primary	Secondary	College	
	25	21	3	
Household monthly income	150,000-500,000	500,000-750,000	750,000+	
	23	17	5	
Person who would decide to buy a solar-powered light	Man only	Woman only	Either	
	24	6	20	
Whether respondent owns a mobile phone	Yes	No		
	49	1		
How much is spent on phone charging per week	5,000	6,000	10,000	
	18	15	1	
Cost of phone, in Kwacha	50,000-100,000	100,000-150,000	150,000+	
	25	11	9	

Translating user preferences into performance requirements

The results of the field research into user preferences were used to define specifications for the minimum features and performance of the product. This translation is subjective in at least two dimensions: first,

[5] Location was a completely off-grid rural community called Kanakantapa, 4 hours from Lusaka. Survey respondents self-selected (all who volunteered to participate were surveyed), N = 50. Not all respondents answered every question; for those questions with exclusive answers, responses that recorded a positive for more than one answer were discarded for that question.

[6] Exchange rate at time of research, June 2009, was 5,100 Kwacha = 1 USD

determining what constitutes "performance" and how that is measured, and second, determining for each measurement of performance what constitutes an acceptable "minimum" level.

Based on previous studies on user preferences for SPLs (Mills 2007; Radecsky, Johnstone et al. 2008), general SPL industry analysis (LADM 2010), and the project team's own assessment, the core performance areas relevant to all SPLs were determined to be: illumination intensity, illumination quality, run time, charge time, and general maintenance. Other possible performance characteristics, such as multiple lighting modes, mobility, and phone charging, were determined to be desirable functionality but beyond the scope of a basic SPL intended to replace candles and kerosene.[7] For each of these five performance areas the project team defined specifications, as summarized in Table 5.

Of these, light output was considered the most important performance criterion to define. Light output is typically measured in one of two ways, based on the type of light and its application: for task lights, such as torches or desk lamps, light is often measured in lux, which can be thought of as the amount of visible light that contacts a surface at a certain distance. For example, a desk lamp may provide 200 lux at 1 meter from the lamp. For ambient lights, output is measured in lumens, which can be thought of as the total visible light being emitted by a lamp in all directions. The relationship between these can be expressed by the form: $1 \text{ lux} = 1 \text{ lumen/meter}^2$. Because the final design was an ambient ceiling light, measurements were based on lumens.

What constitutes "acceptable" light levels depends on many variables, including the type of task, environmental conditions, eyesight of the user, and more (Alstone, Jacobson et al. 2010). Therefore it was decided that the most common existing lighting product—a candle or basic kerosene wick lamp—would serve as a baseline indicator of minimally acceptable light output. Laboratory measurements for typical

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[7] This is not a critique or examination of the value to the customer for these kinds of features. It could very well be that the most successful solar-powered lights will turn out to be those that include phone charging.

kerosene lamps show that light output can vary significantly based on lamp type, wick size, and quality of kerosene, but has been measured at approximately 8 lumens for a basic wick lamp (Mills 2003). The team assumed that any new product, especially one that featured solar and LED technology, would have to outperform existing lighting options, leading to a minimum acceptable light output for the product defined as 15 lumens.

Table 4. Sampling of different light sources and lumen output

Light source	Power	Luminous flux
Incandescent light bulb	100W	1700 lumens
Fluorescent tube light T8	32W	3000 lumens
Fluorescent lantern	6W	340 lumens
LED flashlight	1W	40 lumens
Kerosene wick lamp or candle	n/a	8 lumens

The daily runtime requirement determined product charging and energy storage requirements. Based on user responses about their current kerosene and candle usage patterns, 4 hours was established as the required nightly runtime for the product. This meant that the product needed the capacity to sufficiently charge the battery in one day to provide 4 hours of runtime. The average peak sun hours for Zambia was estimated at 5.5 hours (NASA 2008).[8]

Almost all research participants were familiar with using batteries in electronic devices, and many inquired about the type of battery that would be used, how long it would last, and whether it could be

[8] Based on Lusaka's longitude and latitude. Peak sun hours means the equivalent number of hours per day when solar irradiance averages 1,000 w/m2. Put differently, 5.5 peak sun hours is equal to an average of 5,500 Watt-hours/m^2 per day. Importantly, while there is seasonal variation of insolation in Lusaka, the month with the least, June, still averages 5.2 peak sun hours. See Appendix C for complete data.

replaced. There was clear familiarity with battery charging issues, particularly related to low-quality batteries and imported LED products. Respondents reported that low-cost lights from China, typically non-solar rechargeable LED torches, tend to experience problems with battery charging and circuit failure, leading to customer skepticism. Other research (Mills and Jacobson 2008; LADM 2010) supports the idea that low-quality products are currently spoiling the market in sub-Saharan Africa. Therefore the UC Davis project team decided that the design should include a "smart" circuit and charging function, which protects the battery from overcharging, deep discharge, and accidental discharge. This functionality prolongs battery life, and because replacement batteries constitute the only operating cost of the product, has a significant effect on total cost of ownership.

Table 5. Key performance specifications of final design

Performance area	Specification	Rationale
Illumination intensity	Provides a minimum 15 lumens of usable light	Equal to or slightly better than light output of kerosene wick lantern or candle
Illumination quality	Provides light that is warm in color (<4000K) and maintains constant brightness	Users prefer warm color; circuit is designed to maintain constant brightness (minimizes fading with battery power)
Run time	Runs for at least 4 hours on a charge	Majority of users indicated nightly usage of 3-4 hours for kerosene lantern or candle
Charge time	Re-charges in 1 day	Required for daily use; based on Zambia's latitude and average of 5.5 hours peak sun daily
Maintenance	Includes smart charge protection: Automatic low-voltage shut-off to prevent damage to battery, overcharge protection, sunlight-sensor to prevent accidental draining of battery if light is left on	Charge protection increases battery life and helps to differentiate product from cheap imports that are spoiling the market
Maintenance	Uses standard, widely available AA battery type	Enables users to replace the battery themselves without tying them to proprietary technology

Determining cost constraints

Analyzing lighting expenditures from the customer perspective was important in order to understand the cost constraints that would make the new design “affordable” for users in Zambia. As an inherently relative concept, affordability has no absolute metric or benchmark. In the context of low-income customers of the Global South, Anderson & Billou (2007) define it as “the degree to which a firm’s goods or services are affordable to [base of the economic pyramid] consumers”; noting also that due to the cash flow constraints of daily wages, for many low-income households the upfront cost is the real barrier. For relative measures of affordability, one successful social entrepreneur working in health services used a heuristic target to define affordability of health products as a price equivalent to the average monthly income of those in the bottom 60% of the income bracket (Koch 2006). Of course, an important dimension of affordability is access to alternatives: where a medical device or a mobile phone might not have viable alternatives, and thus could still be seen as affordable despite relatively high prices, a solar-powered light is competing with well-known, low-cost alternatives in candles and kerosene and therefore faces more price pressure. Another relevant example of this challenge are fuel-efficient cook stoves, which compete with traditional cooking methods and devices.

The project team therefore made its assumptions about affordability based on customers’ costs of using existing alternatives, and validated this with informal interviews. For kerosene and candles, average household expenditures in five sub-Saharan countries surveyed by the World Bank ranged from $2.63 - $4.64 per month; these expenditures represent operating costs and do not include the initial investment cost of purchasing a lantern (LADM 2009; LADM 2009). The author’s research in Zambia indicated total monthly household operating costs ranging from $4-$8 per month, with insignificant difference between candle users and kerosene users. Upfront costs for fuel-based lighting products include the purchase price of the kerosene lamp and wick, while candles are essentially a self-contained fuel so the purchase price is considered an operating cost. Kerosene hurricane lamps with glass enclosures cost $2-$5 in Zambia, while basic kerosene wick lamps—typically fashioned from tin cans or other discarded material—can be purchased for less than $0.25. Standard candles cost 700-1000 kwacha, or approximately US$0.14-$0.20, and last 1 to 2 nights, depending on size and quality of the candle. Most households report using multiple instances of either kerosene lamps or candles, typically with one instance in each room being lighted. Some respondents reported carrying a kerosene lamp or candle from room to room, though this was less common.

In focus groups conducted by the project team, most users of kerosene and candles were aware of the high operating costs they pay compared to those with grid electricity. They also understood that solar-powered lights are cheaper to use compared to kerosene or candles, but they could not afford such a large initial investment. While kerosene and candles have relatively high operating costs, these expenditures can be broken down into affordable increments (i.e., individual candles, or 100 mL of kerosene) that can be purchased as needed, similar to how small satchels of detergent or a few minutes' worth of mobile phone talk time are purchased. Compared to solar-powered lights, the barrier to entry for kerosene or candles as initial investment cost, is low enough to make them accessible to even the very poor.

Basing estimated affordability on the payback of that initial investment—where the avoided costs of fuel add up to the purchase price of the SPL—provides a more contextual measurement compared to absolute dollar figures. Paul Polak has suggested that a payback period of 5 months for a solar lantern is acceptable for many low-income households (Polak 2008). For a small SPL such as designed by the UC Davis project, the payback calculation was based on the operating costs of a single candle that the SPL would replace—not the total monthly expenditure on all lighting, which would include simultaneous instances of lighting. Given that target customers in Zambia were candle users paying $2-$4 per month for each candle they kept lit, a payback period of 5 months would require a final retail price of $10-$20. This price range was supported anecdotally through unstructured interviews with candle users, few of which said they were able or willing to pay more than $10 for an SPL without a payment plan. Of course, a stated "willingness to pay" response in a survey or interview may not correlate to actual purchase behavior.

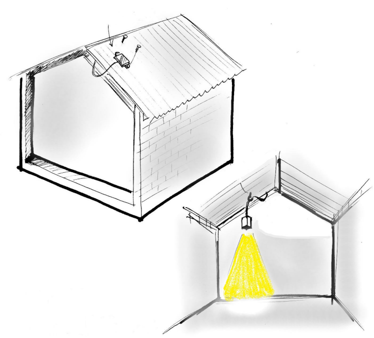
Final design characteristics

The project team used the user preferences, performance specifications, and cost constraints, and plugged these into a basic user-centered design approach, whereby the needs and preference of the user serve as the foundation for design decisions (IDEO 2009). Because the underlying technology used in solar portable lights is well understood, the design challenge was to determine an optimal form factor and then select the combination of components that most effectively produced the required performance within the cost constraints. This section includes discussion of the final product form factor and features, followed by an optimization exercise that was used to select the best combination of key components.

Form factor and general components

Based on input from the focus groups, the project team decided that ambient lighting could serve more needs than focused task lighting (e.g., torch or desk lamp) and therefore have a more compelling value proposition for the customer. In terms of form factor, it was determined that a hanging overhead light could maximize the usable light emitted due to virtually 100% of the light being directed down toward the user, mimicking the basic “light-bulb-on-a-wire” ceiling lights common to many electrified homes in Zambia. This configuration is supported by modern LED designs, where an angle of illumination of 120 degrees is common.

Figure 1. Final product: A household light that mimics ceiling lights in grid-powered homes



The final design (Figure 1) comprises a small solar panel, to be hung on the roof or in a window, connected with a 4-meter wire to the light body, or luminaire. The length of wire and installation requirements were validated against common house dimensions in Zambia, as well as by a building engineer for Habitat for Humanity, a large NGO focused on construction of low-income housing in compounds outside of Lusaka. While the product can perform as a conventional hanging ceiling light, the wire has an inline connector (standard DC plug of a type used on many consumer electronics) so that the luminaire can be disconnected from the solar panel and used in another room or as a mobile light. The team had sought to distinguish the product from a torch due to reported customer association of the torch form factor with lower-price and lower-quality products (LADM 2009). However, in focus groups there were strongly expressed requests for mobility, which was enabled by the addition of the inline connector. The single battery is a rechargeable NiMh AA, a common, non-proprietary battery type that can be replaced by the user. A simple on-off switch controls operation; there are no variable lighting modes. The lamp itself is a high-efficacy surface-mount LED.

In order to maximize the generalizability of this product design research, the key components are grouped into six basic “elements” that are common across many solar portable lights: 1) solar cell for converting sunlight to electrical energy, 2) battery for energy storage, 3) LED lamp for illumination, 4) electronic circuitry for controlling operation, 5) external wiring, and 6) case and packaging. Table 6 indicates the key considerations for each element.

Table 6. Key components in the product design

Element	Considerations
Solar cell	• Must deliver sufficient power to charge 1.2V battery in 5.5 hours of average peak sun hours in Zambia • Resistance in wiring can be significant at low voltages and must be accounted for • Amorphous silicon, common for this size, is cheaper but less efficient than polycrystalline • Epoxy-coated solar cells yellow with exposure to sun, decreasing efficiency within 2 years; PET-laminated lasts longer but has higher cost

	• Glass cover and aluminum frame extend cell lifespan, but have higher cost
Battery	• Charging capacity should be oversized from daily requirements in order to provide a buffer for cloudy days, which extends the working life of the battery • Battery types evaluated over cost, energy density, deep discharge tolerance, self-discharge rate, toxicity and other parameters; nickel-metal hydride (NiMh) was deemed most appropriate • AA form factor is nonproprietary, available globally • Single battery avoids user uncertainty in replacement • Battery lifespan = 50% capacity after 500 cycles
LED	• Efficacy (lumens-per-watt) is significant factor in overall product performance • LEDs typically designed to run in specific power range • Lower-quality LEDs can have significant variations in performance and color[9] • Color temperature can be an issue—cooler white is cheaper than warm white for the same light output; user preferences may depend on familiarity with fluorescent lighting
Circuitry	• Energy-efficient design is critical for low-power application • Selection of LED driver / integrated circuit changes efficiency • Circuit should deliver constant current for optimal LED operation[10] • Single-sided PCB reduces fabrication costs, but total surface area is more significant • Surface-mount components are cheaper for automated assembly, but may preclude manual assembly • Switch quality is important, especially given various environmental conditions
External wiring	• Sufficiently small resistance for low-power DC current • Molded connector with appropriate grab strength and durability
Case and packaging	• Injection-molded plastic housing with removable cover • Simplified geometric case design has lower tooling cost, additionally this minimizes material usage for lower per-unit costs and shipping costs • Basic packaging minimizes material for lower per-unit costs and shipping costs • Simple cardboard box with paper insert

System cost optimization: methodology

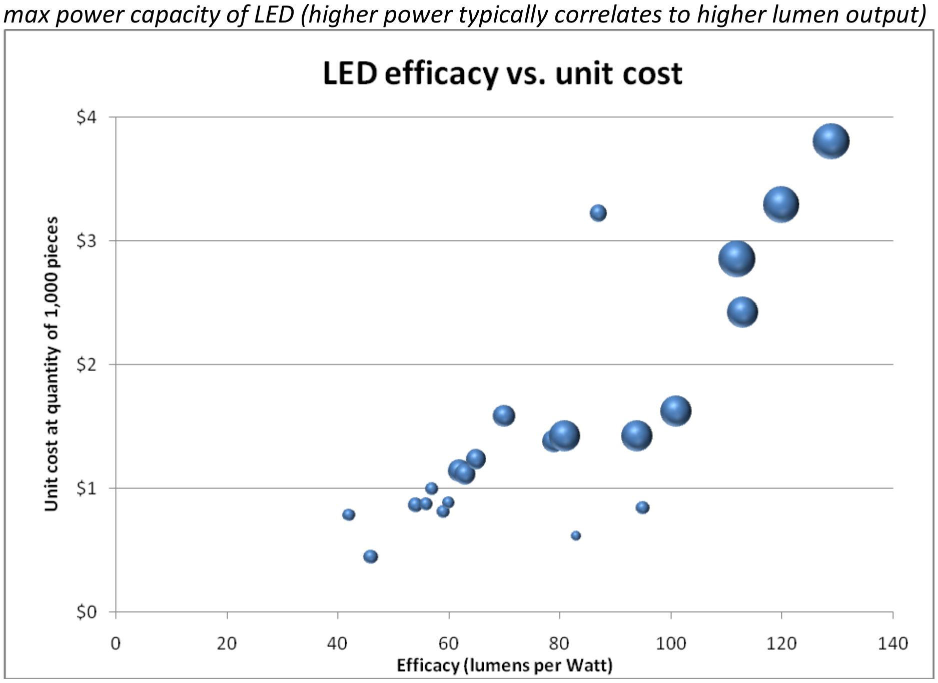
In general for a given element, such as the LED, an increase in performance or efficiency comes with an increase in cost (See Figure 2). However, these increases are not always linear, and due to the dependencies and specific interactions between components, it is not always apparent which element combination will offer the most cost-effective performance for the product as a whole. Thus the project team performed an optimization exercise to determine the most cost-effective combination of elements.

[9] See Mills, E. and A. Jacobson (2008). "The Need for Independent Quality and Performance Testing of Emerging Off-grid White-LED Illumination Systems for Developing Countries." Light & Engineering **16**(2): 5-24.

[10] Ibid.

It should be noted that due to multiple specifications of each individual component, and differences in quality that may or may not be reflected in the measured performance, it was not within the scope of this exercise to incorporate all individual component characteristics into the analysis. For example, one type of wiring may have a more durable plastic sheath, or a certain type of solar panel may have better solder pads on the back for attaching the wiring. While these kinds of features play a role in ultimate part selection, they were not considered in this analysis.

Figure 2. LED efficacy and cost for specific power range. Bubble size indicates max power capacity of LED (higher power typically correlates to higher lumen output)



To conduct the optimization, the team first defined the basic circuit parameters, such as battery type and LED driver, which would be held as constants. Based on this, the team established a range of performance specifications that would be relevant to explore for each of the following four elements: 1) solar cell, 2) battery, 3) LED, and 4) external wiring. These four were selected based on whether the element a) has a significant effect on overall performance, and b) is a discrete component that can be substituted in and out of the circuit. Note that the wiring is significant given the low voltage (2V direct current) and length (4 meters). Other components, such as the LED driver/IC, also play a large role in overall product performance but are integrated too tightly into the circuit design to enable the substitution of different models with varying performance and pricing. For each element three different values, or "tiers," were identified, and the associated performance and cost characteristics were determined (Table 4). The values tested were based on actual products with performance characteristics within the range deemed viable, based on preliminary testing. Because the function of the circuit is essentially the same for all element combinations, a single function was used to predict performance and cost for each of the 81 (i.e., 3^4) combinations considered (Table 5). Lumen output was normalized across all combinations at 18 lumens (which met the performance requirement of >15 lumens) so resulting runtimes and costs were the outputs for comparison.

Table 7. Elements tested in optimization exercise

Element	Variable	Units	Values tested		
PV cell	Current	Amps	0.25	0.30	0.35
Wiring	Resistance	Ohms	0.67	0.42	0.27
Battery	Capacity	Watt-hours	1.8	2.04	2.4
LED	Efficacy	Lumens/Watt	46	60	90

Table 8. Assumptions and constants

Assumption	Value
Voltage of PV cell (V_{mp})	2
Charging efficiency of NiMh battery	66%
Daily peak sun hours	5.5
Efficiency of circuit	85%
Nominal voltage of AA battery	1.20

Calculations

The following relations were employed to calculate product performance:

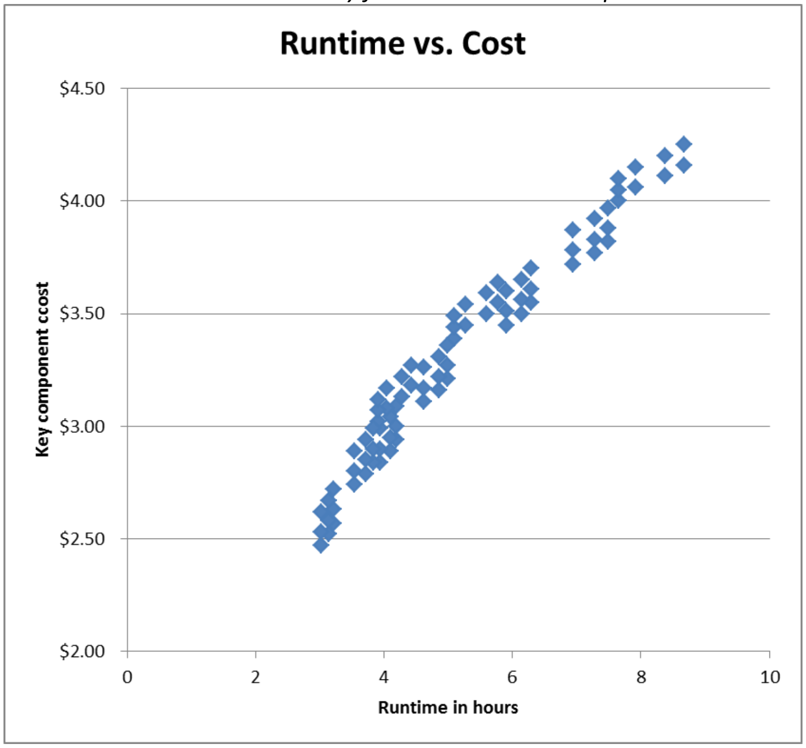
(PV power – diode loss – wiring loss) * charge eff. of battery * daily sun hours = Watt-hours per day into battery (1)
Lumen output = 18 lumens = power to LED * LED efficacy (2)
Watt-hours per day into battery * circuit efficiency / power to LED = runtime in hours per day (3)

Note that equation (2) was used to normalize all combinations to a set lumen output, designated at 18 lumens, by adjusting the amount of power sent to the LED. Clearly, more efficient LEDs use less power to achieve the 18 lumens, and therefore were run at lower power. The 'power to LED' value was then plugged into equation (3) to determine 'runtime.' For each combination the individual component costs were summed to determine cost-effectiveness for that combination relative to runtime.

Optimization results

The 81 combinations showed a range in runtime from 3.0 to 8.7 hours, with 57 combinations delivering the minimum requirement of at least 4 hours runtime (see Figure 3). The combination that ran for 8.7 hours cost 63% more than the lowest-cost combination, but provided almost triple the runtime. To determine the optimal configuration, the cost of each combination was divided by the daily lumen-hours it provides (because all combinations were set to 18 lumens, this is essentially equal to the runtime), providing a metric of "dollars per lumen-hour." Note that this metric is only meant as a relative measure within this optimization exercise—the cost used only represents a subset of the components in a complete SPL, and the cost is not amortized over time as in a "levelized cost of electricity" metric—so this discussion does not focus on the actual dollar figures. Nevertheless this metric provides a guide for the most cost-effective combination, which included the most expensive LED, wiring, and solar panel, and the 2nd most expensive battery. See *Appendix D* for a table showing the results of the 81 combinations, as well as additional graphs showing component performance vs. cost.

Figure 3. Runtime plotted against cost for each of the 81 combinations; note that cost shown here is only for the 4 selected components



All of the top combinations in terms of dollars per lumen-hour used the most expensive (and most efficient) LED, demonstrating that the LED was the most cost-effective component to invest in—extra dollars spent on the LED resulted in better performance gains, all else held constant, than any other tested component. These findings support general energy efficiency theory—given that the LED is the final component in the circuit in terms of electricity flow, for every efficiency gain to the LED, every component upstream of the LED runs with lower power and current and can often be downsized in performance and cost. The project team used the results from the optimization analysis to select specific models for each of the components tested. Specifically, the team modified the initial design to include a higher-efficiency LED, a lower-capacity battery, and optimized resistance for the external wiring.

Cost analysis

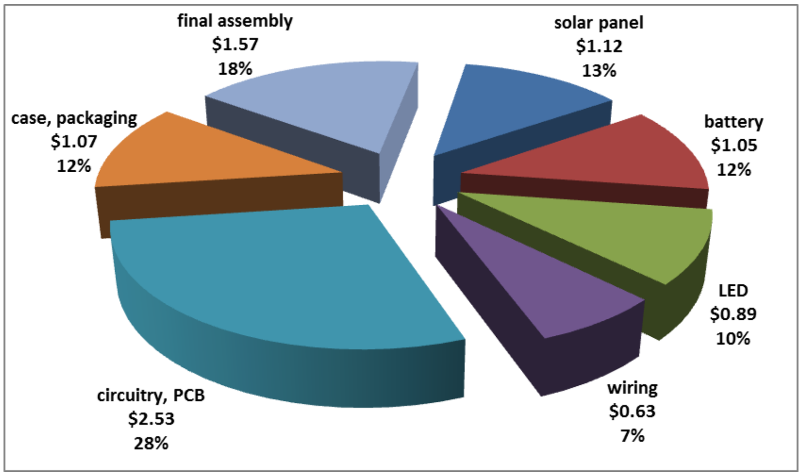
Production costs

Once the final design was prototyped and tested with users, the project team hired a Hong Kong-based engineering firm to manage sourcing and manufacturing in Shenzhen, China. The manufacturing of the light occurred in September of 2010. This cost analysis therefore represents actual costs paid by UC Davis for production of 1,500 units.

The total variable costs of production were $8.86 per unit[11], approximately $2 higher than originally estimated. Breaking down costs into the six categories (plus assembly) confirms the importance of the four key components included in the optimization exercise (solar panel, LED, battery, and wiring), as they are the four most expensive components and represent approximately 42% of the total unit cost (see Figure 3). Because these costs are based on low-volume manufacturing of only a few thousand units, there would be significant decreases in pricing for higher quantities. In particular, the passive electronic components (e.g., resistors, switch, etc.) that contribute to the “circuitry” category would likely see significant price reductions in larger volumes. In addition, the cost of assembly would see large price reductions as volumes increased: The UC Davis industrial design was not optimized for automated processes, and therefore required hand assembly work such as stripping wires, threading wires through the plastic cabinet and PCB, hand-soldering through-hole components, and hand-soldering wires to the solar panel. A more sophisticated industrial design could eliminate many of these elements.

[11] Note that the cost structure of the final light design does not include tooling or set-up costs, only the direct, variable costs of the materials, assembly, and packaging, in effect the per unit “FOB” (freight on board) cost of the complete product ready to be shipped. This product required approximately $6,000 in tooling costs for the injection molds. Once shipping, insurance, taxes, and distributor margins are factored in, the retail price may be approximately double, depending on the target market for distribution.

Figure 4. Cost structure of final design. Total cost: $8.86



The cost breakdown by category shows some similarities to an LADM industry survey of SPL production costs (LADM 2010). Because the categories used in the LADM study do not exactly match with this case study, and the data comprising those categories were not available, it is not possible to provide an apples-to-apples comparison for all components. For example, the LADM study groups assembly costs with the case, but it's unclear if these are just final assembly, or include PCB assembly. What is apparent is that the median SPL on the market today uses much larger and costlier solar cells, batteries, and LEDs, resulting in a total manufacturing cost of about $19.50 vs. the UC Davis cost of $8.86. This large difference in component size (e.g., a 2.5W solar cell for industry median vs 0.5W for UC Davis) will largely translate into performance gains.

It is interesting, however, that the increase in size and performance does not seem linear in respect to percentage of overall costs. For example, in the industry median cost structure the solar cell accounts for almost 1/3 of the cost, and the solar panel for almost 1/4 of the cost. That this ratio doesn't hold when the entire product is scaled down suggests that there is some cost "floor" or minimum costs that are unavoidable even when the performance is scaled down. Some of this could be in the active electronic components—for example, a $0.34 integrated circuit/driver is the minimum needed, whether the solar panel is 5W and sending high levels of current or the panel is 0.5W and sending low amounts of current.

Most of this minimum cost is likely in the final assembly costs, where the level of skilled labor and the amount of time it takes to solder solar panel leads is similar no matter the size of the panel. Obviously, the higher the volume or quantity of a given product, the lower the assembly costs, and the UC Davis product pricing shown was for very small quantities of 1,500 units.

Table 9. Comparison of UC Davis costs vs. industry medians (LADM 2010)

UC Davis SMART Light		
solar panel	$1.12	13%
battery	$1.05	12%
LED	$0.89	10%
wiring, circuitry	$3.16	35%
case, packaging	$1.07	12%
final assembly	$1.57	18%
Total	$8.86	100%

Industry medians		
solar panel	$6.10	31%
battery	$4.50	23%
LED	$3.70	19%
circuitry	$2.70	14%
case, assembly	$2.50	13%
Total	$19.50	100%

Production cost projections

The market for off-grid lighting solutions is expected to grow at a significant rate, with one estimate of 40%-65% year-on-year growth in Africa through 2015 (LADM 2010). As more organizations enter the market to meet this demand, manufacturing costs will decrease as volumes rise. In addition, global demand for the core technology of SPLs—solar PV and LEDs—will continue to drive improvements in manufacturing and technology advances for those specific components, leading to even lower prices and costs of production. As a result, LADM estimates a 40% overall reduction in manufactured cost for SPLs by 2015, with the majority of that reduction coming from advances in LED technology (LADM 2010).

In the laboratory, LEDs have broken the 200 lumens-per-watt barrier (Cree 2010), and production LEDs have reached over 150 lumens-per-watt. While the top-performing LEDs are likely outside the cost range for most SPLs, these advances in performance drive down costs of lower- and mid-range power LEDs. In terms of the solar cell, global demand will lower prices of mono- and poly-crystalline cells in general, but the small size of the typical SPL solar cell will likely always incur a much higher per-watt price compared to larger SHS-scale or utility-scale solar panels in the 100+ watt range. Perhaps more interesting are developments in amorphous silicon and other types of thin-film PV technology. While less efficient than crystalline forms, thin film is typically much less expensive to produce, and its flexibility and light weight can provide distinct advantages in shipping and distribution.

Customer costs

While this study focuses on costs of production, it is also important to evaluate affordability from the customer's perspective. Key costs for the customer are: upfront cost (first cost, or retail price), operating costs (running costs), and total cost of ownership (TCO, the sum of all costs over the lifetime of the product). The retail price will be cost of production, plus some combination of shipping, insurance, freight forwarding, import duties/tariffs, VAT, distributor margin, retailer margin, and other costs. A common rule of thumb for estimating retail price is to double the cost of production. For example, Mills et al. (Mills 2007) estimated that a solar-powered light landing in Mombassa, Kenya, that cost $45 to manufacture would sell for a retail price of $85 (see Table 10). LADM also estimates a rough doubling of manufactured cost to arrive at final retail price, though it assigns a larger margin to the retailer (LADM 2010). Using these numbers, the UC Davis SMART Light with a manufactured cost of $8.86 would have a retail price of approximately $16.56. Given the relatively poor infrastructure and landlocked nature of Zambia, the project team estimates the retail price will be closer to $18-$20.

Table 10. Mills' estimated additional costs for distribution in Kenya

Additional costs incurred (cumulative)	
Shipping, handling, insurance	11%
VAT	16%
Import duties	10%
Distributor margin	20%

Retailer margin	10%

To relate the customer's financial costs to actual light output, measured in lumens, there are a number of different metrics used in the literature (Mills 2003; Peon, Doluweera et al. 2005; Mills and Jacobson 2008). The author used a measurement by Mills and Jacobson (2008), "dollars per 1000 lumen-hours," which expresses the total cost of ownership of a product over its stated lifetime to the amount of useful lighting service produced. With a two-year lifetime, the final design delivers light at the rate of $0.27 per 1000 lumen-hours as shown in Table 11. This compares to $2.18 per 1000 lumen-hours for a candle and $1.87 per 1000 lumen-hours for a basic kerosene wick lamp.

Table 11. Inputs for determining cost per unit-of-service for final design

Metric	Value
Product retail cost	$18
Product lifetime	2 years
Operating cost (battery replacement)	$2
Total cost of ownership	$20
Lifetime light output	52,560 lumen-hours
Cost per unit-of-service	$0.27 per 1000 lumen-hours

Assumptions:

1. Battery replacement required after 1.5 years, single battery cost is $2
2. Daily operation is 4 hours
3. Light output is 18 lumens
4. Kerosene: burn rate = 13 liters/year, cost of kerosene = $1.50/liter, cost of wicks = $1.42/year, cost of lamp = $1, lifespan of lamp = 1 year, luminous flux = 8 lumens
5. Candle: burn rate = 0.5 candle/day, cost of candle = $0.14, luminous flux = 8 lumens[12]

[12] Using the kerosene lamp burn rate and light output established by Mills (Mills, 2003). All costs adjusted for Zambia, including prices for kerosene as typically purchased in small quantities with associated markup.

While the cost-per-service comparisons to kerosene and candles are overwhelmingly positive for the final design, this is invariably the case with solar powered products measured over their lifetime. As noted in the introduction, the objective of the UC Davis project was to design an SPL that could be purchased without financing in order to improve chances of adoption. Estimating this affordability threshold is difficult and very context-dependent, which leads to using the idea of payback period (amount of time for the avoided costs of paying for candles/kerosene equal the upfront cost of the SPL) as a proxy for affordability. However, it may be that the only real test of affordability is whether customers purchase the product.

Research limitations

The research methodology for understanding user preferences lacked scientific rigor, with two primary causes: First, the UC Davis project team did not set up an adequate structure and framework for conducting the research, both when onsite and when trying to manage the research remotely. For example, criteria for which communities to sample were too vague, leaving too much room for subjective selection by the researcher. This specific issue is complicated by the logistical constraints of a small study, where truly random selection or larger sample sizes were out of scope given the budget and time available. Secondly, the training of the Zambian staff was insufficient in training them to perform objective research. Without clear structure and specific guidelines—for example, how to avoid selection bias in survey subjects, how to avoid asking leading questions during an interview, etc.—the staff collected data in a manner that could be considered casual in nature. While these failings on the part of the UC Davis project team, primarily of the author, are a clear deficiency, the data that was collected does align with the vast majority of the published results of larger studies such as the World Bank LADM.

Additional discussion

Industrial design considerations

While the stated emphasis throughout the design process was on eliminating costs for increased affordability, there were at least two instances when the team elected for a more expensive design. The initial prototypes were not meant to be mobile—the light was hard-wired to the solar panel—but when user-tested in Zambia, there were overwhelming calls for the light to be detachable. This necessitated the addition of an inline connector (ultimately a standard DC plug was chosen) that added at least $0.35 to the BOM. The second instance of cost-cutting that was reversed in the final design was for the plastic cover over the circuit board. The later prototypes included a 1mm-thick piece of clear sheet plastic cut to fit over the circuit board and kept in place with small tabs. User feedback was that this design was ugly, and made the product appear low-quality. For the final design, the team had an additional injection mold built, and the cover is now made out of a piece of injection-molded ABS similar to rest of the case. This change probably only added around $0.15 per unit in materials cost, but required approximately $2,000 in additional capital for the injection mold tooling. The lesson learned is that a complete focus on reducing cost can be counter-productive if it reduces the value proposition for customers; continuous and iterative user testing can mitigate this possibility.

The role of quantity in the SPL design

Due to volume pricing, the costs of production for building 1,000 SPLs may be 10%-20% higher than the per-unit cost of building 50,000 SPLs. Production quantity will also affect decisions on tooling or production processes. As an example, the injection mold for the plastic case could be machined out of different types of metals with varying hardness, with the harder materials costing more to make into molds but lasting longer. If a production quantity is known, then amortizing the capital costs over time can provide guidance for this decision, but this is more difficult for new products without clear estimates of quantity. In terms of production processes, whether to use manual or automated manufacturing depends mostly on quantity, but also on the cost and skill level of available labor, the degree of quality control and uniformity required, the desired impact on employment, and the time available. The project team found that semi-skilled labor for tasks such as assembling circuit boards and manual injection molding of plastic were cost-competitive with automated processes at volumes of only a few thousand units per month.

SPL value proposition also depends on performance, quality, and other non-cost issues

While this article has focused on costs of production and therefore retail price as the key factor in affordability of SPLs, there are clearly many factors that affect adoption and long-term success of the SPL market. User preferences in terms of form factor, features, user interface, and branding, all play significant roles. The market for SPLs and other energy services is diverse, with customers from very different income levels, geographic locations, and cultural norms. Already the market is seeing specialization as manufacturers find and serve niche customer segments, and this trend is likely to continue with more user-centric design (LADM 2010). Of course, product design is only half the equation. Even a well-designed product that meets users' needs cannot succeed without successful marketing, distribution, financing, and operational support.

Need for quality control, standards, testing in the SPL market

Because of the pervasiveness of inferior lighting products and market poisoning, quality is a key concern for consumers and manufacturers alike, as savvy consumers are demanding warranties to protect their investments. Respondents to our research in Zambia frequently inquired about the warranty, assuming there would be one and stating they would not consider a purchase without one. There is a large push for the establishment of industry standards and quality assurance programs by LADM in conjunction with the Lumina Project. The latter has established basic performance testing criteria, including measurements of luminous flux, spatial variation of illuminance, frequency of charging as function of desired light per day, and more (Mills and Jacobson 2008).

Conclusions and further research

Through field research and user testing of prototypes in Zambia, it was determined that a solar portable light with light output at least as bright as a simple kerosene lamp or candle that could run for 4 hours on one day's charge would be acceptable to many users. Translating user preferences into functionality and performance requirements is essentially a design process, with inherent subjectivity that is difficult to mitigate. Using a more formal and rigid design methodology could have eliminated some subjectivity, but even in selecting a methodology the designers are making decisions about the outcome. Within these constraints, it was determined that an SPL could meet the basic performance requirements of users with a 0.5W solar cell, 2000 mAh AA battery, and 60-lumen/Watt LED in a standard plastic housing. An optimization study revealed that specifying a higher-efficacy LED reduces the product cost by lowering the power requirements of the PV cell, battery, and wiring, therefore making the LED the most cost-effective component to focus on.

This minimal configuration can be manufactured in China for less than $9 per unit at low quantities of less than 10,000 pieces. This translates into an estimated retail price of $18-$20 in Zambia, or a simple payback period of 5-10 months depending on candle usage. This payback period probably puts this SPL out of reach of many low-income households in Zambia, which might require a payback period of 3 months or less.

The specified manufacturing cost can definitively be lowered through higher-volume manufacturing, which would specifically decrease the costs for passive electronic components and final assembly. In addition, advances in solar cell and LED technology and manufacturing processes promise steadily decreasing costs for components over the next 5-10 years.

Further research is needed to understand the value proposition of solar-powered lighting for off-grid users of fuel-based lighting. This project examined user preferences and translated these into a low-cost SPL design that, in theory, meets users' needs. Additional study of user reaction to the final design—Will people purchase it? Who will and who won't? And why?—is necessary for a more complete picture of this SPL's affordability and success in meeting user needs. Moreover, it may be that focusing only on lighting end-use may miss the greatest opportunities for widespread adoption of off-grid solar power: Many, if not most, households in Zambia have at least one mobile phone that requires charging from an electrical power source, which is typically expensive and inconvenient for rural households. Numerous solar-powered lighting systems, especially SHSs, include mobile phone charging as an additional feature, and in our research, one of the first questions asked in focus groups or interviews was "Will this charge my mobile phone?" Therefore lighting products that incorporate or facilitate mobile phone charging may have a higher chance at success than lights alone.

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Appendix A. Customer survey instrument

Lighting the Way
Customer Survey - v.3

Date: ________________
Community name: ________________
Community population: ________________
Distance from Dhaka: ________________
Facilitator: ________________
Self-completed: ________________

LIGHTING USAGE

1. What do you use for lighting? Circle more than one if necessary.

   Paraffin/Kerosene   Candles Torch (with batteries)

2. How many people, including children, live in your house?

   1   2   3   4   5   6   7   8+

3. How many kerosene lamps or candles do you light at the same time?

   1   2   3   4   5   6

4. Who purchases the candles/kerosene?

   Man   Woman

5. How many times per **month** does the man or woman buy candles/kerosene?

   1 x per month   2x per month   3x per month   4x per month

6. How many kilometers from your house is the shop where you buy candles/kerosene?

   0-1 km   1-3 km   3-8 km   8-15 km   15+ km

7. How much money do you spend per **month** on candles/kerosene?

   100-150 t   150-250 t   250-500 t   500-750 t   750 +

8. What activities do you and your family do at night using the light?

Visiting Homework Cooking Business Other

9. Do your children light the candles/kerosene by themselves?

Yes No

10. How many hours per night do you use lighting?

1-2 hours 2-3 hours 3-4 hours 4-5 hours 6+ hours

11. Have you seen a solar panel being used?

Yes No

12. What is your roof made of?

Iron Asbestos Grass

13. How would you rate your ability to speak English?

Very good Good Okay Poor

14. How would you rate your ability to read English?

Very good Good Okay Poor

15. How many years of school have you completed?

None 1-3 years 4-6 years 6-10 years University

16. What kind of work do you do for income?

____

17. In which month does your household have the most income?

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov

18. About how much income do you think your household could earn in a month?

____

19. What is one advantage of solar lighting over candles/kerosene?

____

SMART LIGHT

20. How much would you pay for the SMART Light?

    250 taka 500 taka 750 taka 1000 taka 1500 taka

21. Who would make the decision to buy a SMART Light?

    Man Woman

22. Where do you think the SMART Light should be sold?

    ____

23. What kind of warranty would you want?

    ____

24. If the price was good, why would you buy a SMART Light?

    ____
    ____

25. Do you know where you can buy rechargeable AA batteries?

    Yes No

MOBILE PHONE

26. Do you have a mobile phone?

    Yes No

27. How much did the mobile phone cost to purchase?

    500-100 t 1000-1500 t 1500-2000 t 2000-3000 t 3000+

28. How and where do you charge it?

    ____

29. How much does it cost to charge it?

    ____

Appendix B. Sample field report from Zambian staff

LIGHTING THE WAY

WEEK 1, 2 AND 3-DECEMBER 2009 REPORT

The following activities were undertaken in the following peri urban areas:

- CHUNGA
- GEORGE
- JOHN LAIGN
- DESAI
- CHAWAMA
- KANYAMA
- NGOMBE
- KALIKILIKI
- LUSAKA WEST
- CHAISA

The purpose of this research was to conduct interviews with fifty people. These people have no connection to the ZESCO grid and have no possibility of having electricity in the next five years.

The interviews were done and it was discovered that most people in peril urban use candles against kerosene. The reason being that candle is available on the market and is safe to use than kerosene. To find and buy kerosene, one needs to go to the fuel filling station. This is a discouragement so to some people as it is better to buy a commodity which is nearer than that from far. Candles are sold in nearer shops than the Kerosene. Candle is well advertised on the Zambian market with most people knowing a better brand.

In the above communities they buy candles on a daily basis and some do it weekly.
The price of small candle is K500.00 (Five hundred kwacha)
The price of medium candle is K700.00 (Seven hundred kwacha)
The price of big candle is K1000.00 (One thousand kwacha)

Most of the houses have got iron sheet . Most of them are single bed roomed houses.
They charge the cell phones at the place called Tutemba at a cost of two thousand and five hundred kwacha (K2,500) or three thousand kwacha (K3,000). Some have to go and charge to their friends or relatives with electricity in the homes at no cost. Candles are bought mostly between 18 and 19 hours due to the fact that this is when there is a need of lighting. In some homes they share candles by cutting in two or three part so that every one can have light.

The majority uses light for cooking, family meeting, studies and business. They use light between 3 to 4 hours daily. Some people who can not afford candles cook out side when it is not dark; they go some times without using candle light.

Men, women and children are involved in the family buying decision making unit. The women and children influence the man to buy candles, because every one has a need for light. For example the woman would want light for cooking, children will need it for studies and man will need it for eating after work or beer drinking. So we should involve a family in our smart light marketing system.

I visited the television stations to find out on the rates on advertising .The visited stations were Mobi television, Muvi television and the rates are very high that our budget can not accommodate. So we are planning to approach the community radio station and find out how much they charge.

I strongly feel we should continue with research in remote areas and come up with new plans.

Appendix C. Monthly solar irradiance (insolation) for Lusaka, Zambia

Based on NASA Surface meteorology and Solar Energy (SSE) data for latitude and longitude of Lusaka.

Data assumes horizontal inclination ("flat plate").

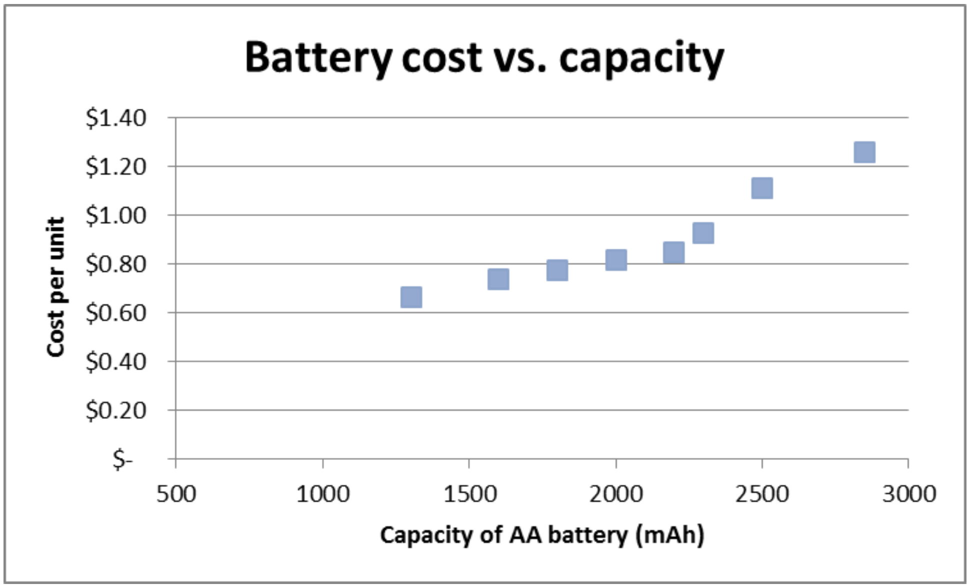
Data online at http://eosweb.larc.nasa.gov/sse/global/text/22yr_swv_dwn

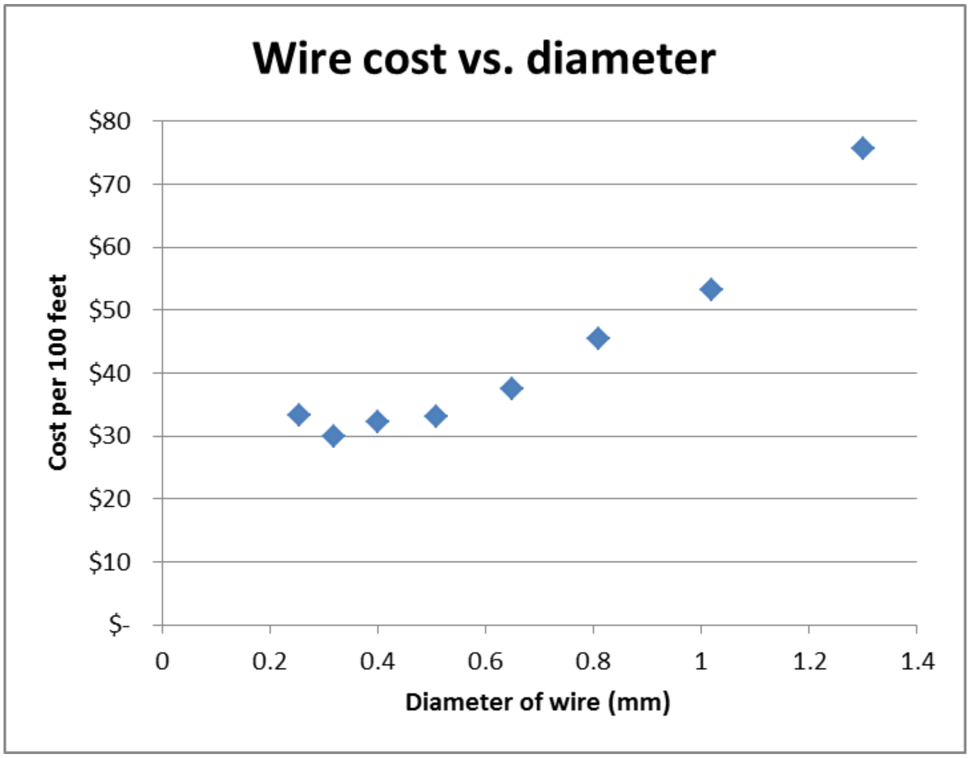
Month	Avg. peak sun hours
January	5.38
February	5.52
March	5.57
April	5.74
May	5.52
June	5.18
July	5.44
August	6.18
September	6.67
October	6.83
November	6.14
December	5.45
Annual	**5.80**

Appendix D. Optimization combinations and additional graphs

Combinations					Calculations							
Comb. #	PV	Wiring	Battery	LED	Wh/day input	Battery constraint	Wh/day available	Power to LED	Runtime	Lumens	Cost	Daily $ /lumen-hour
78	0.35	0.27	2.04	90	2.04	2.04	1.73	0.20	8.67	18	$4.16	$0.0267
69	0.35	0.42	2.04	90	1.97	1.97	1.68	0.20	8.39	18	$4.11	$0.0272
81	0.35	0.27	2.4	90	2.04	2.04	1.73	0.20	8.67	18	$4.25	$0.0272
72	0.35	0.42	2.4	90	1.97	1.97	1.68	0.20	8.39	18	$4.20	$0.0278
48	0.3	0.27	1.8	90	1.76	1.76	1.50	0.20	7.49	18	$3.82	$0.0283
60	0.35	0.67	2.04	90	1.86	1.86	1.58	0.20	7.91	18	$4.06	$0.0285
39	0.3	0.42	1.8	90	1.71	1.71	1.46	0.20	7.28	18	$3.77	$0.0288
51	0.3	0.27	2.04	90	1.76	1.76	1.50	0.20	7.49	18	$3.88	$0.0288
57	0.35	0.67	1.8	90	1.86	1.80	1.53	0.20	7.65	18	$4.00	$0.0290
63	0.35	0.67	2.4	90	1.86	1.86	1.58	0.20	7.91	18	$4.15	$0.0291
42	0.3	0.42	2.04	90	1.71	1.71	1.46	0.20	7.28	18	$3.83	$0.0292
66	0.35	0.42	1.8	90	1.97	1.80	1.53	0.20	7.65	18	$4.05	$0.0294
54	0.3	0.27	2.4	90	1.76	1.76	1.50	0.20	7.49	18	$3.97	$0.0294
75	0.35	0.27	1.8	90	2.04	1.80	1.53	0.20	7.65	18	$4.10	$0.0298
30	0.3	0.67	1.8	90	1.63	1.63	1.39	0.20	6.94	18	$3.72	$0.0298
45	0.3	0.42	2.4	90	1.71	1.71	1.46	0.20	7.28	18	$3.92	$0.0299
33	0.3	0.67	2.04	90	1.63	1.63	1.39	0.20	6.94	18	$3.78	$0.0303
36	0.3	0.67	2.4	90	1.63	1.63	1.39	0.20	6.94	18	$3.87	$0.0310
21	0.25	0.27	1.8	90	1.48	1.48	1.26	0.20	6.30	18	$3.55	$0.0313
12	0.25	0.42	1.8	90	1.45	1.45	1.23	0.20	6.15	18	$3.50	$0.0316
24	0.25	0.27	2.04	90	1.48	1.48	1.26	0.20	6.30	18	$3.61	$0.0319
15	0.25	0.42	2.04	90	1.45	1.45	1.23	0.20	6.15	18	$3.56	$0.0322
3	0.25	0.67	1.8	90	1.39	1.39	1.18	0.20	5.91	18	$3.45	$0.0324
27	0.25	0.27	2.4	90	1.48	1.48	1.26	0.20	6.30	18	$3.70	$0.0326
18	0.25	0.42	2.4	90	1.45	1.45	1.23	0.20	6.15	18	$3.65	$0.0330
6	0.25	0.67	2.04	90	1.39	1.39	1.18	0.20	5.91	18	$3.51	$0.0330
9	0.25	0.67	2.4	90	1.39	1.39	1.18	0.20	5.91	18	$3.60	$0.0338
77	0.35	0.27	2.04	60	2.04	2.04	1.73	0.30	5.78	18	$3.55	$0.0341
68	0.35	0.42	2.04	60	1.97	1.97	1.68	0.30	5.59	18	$3.50	$0.0348
80	0.35	0.27	2.4	60	2.04	2.04	1.73	0.30	5.78	18	$3.64	$0.0350
71	0.35	0.42	2.4	60	1.97	1.97	1.68	0.30	5.59	18	$3.59	$0.0357
47	0.3	0.27	1.8	60	1.76	1.76	1.50	0.30	5.00	18	$3.21	$0.0357
38	0.3	0.42	1.8	60	1.71	1.71	1.46	0.30	4.86	18	$3.16	$0.0361
59	0.35	0.67	2.04	60	1.86	1.86	1.58	0.30	5.28	18	$3.45	$0.0363
50	0.3	0.27	2.04	60	1.76	1.76	1.50	0.30	5.00	18	$3.27	$0.0364
41	0.3	0.42	2.04	60	1.71	1.71	1.46	0.30	4.86	18	$3.22	$0.0368
56	0.35	0.67	1.8	60	1.86	1.80	1.53	0.30	5.10	18	$3.39	$0.0369
62	0.35	0.67	2.4	60	1.86	1.86	1.58	0.30	5.28	18	$3.54	$0.0373
29	0.3	0.67	1.8	60	1.63	1.63	1.39	0.30	4.63	18	$3.11	$0.0374
53	0.3	0.27	2.4	60	1.76	1.76	1.50	0.30	5.00	18	$3.36	$0.0374
65	0.35	0.42	1.8	60	1.97	1.80	1.53	0.30	5.10	18	$3.44	$0.0375
44	0.3	0.42	2.4	60	1.71	1.71	1.46	0.30	4.86	18	$3.31	$0.0379
74	0.35	0.27	1.8	60	2.04	1.80	1.53	0.30	5.10	18	$3.49	$0.0380
32	0.3	0.67	2.04	60	1.63	1.63	1.39	0.30	4.63	18	$3.17	$0.0381
20	0.25	0.27	1.8	60	1.48	1.48	1.26	0.30	4.20	18	$2.94	$0.0389
11	0.25	0.42	1.8	60	1.45	1.45	1.23	0.30	4.10	18	$2.89	$0.0391
35	0.3	0.67	2.4	60	1.63	1.63	1.39	0.30	4.63	18	$3.26	$0.0392
23	0.25	0.27	2.04	60	1.48	1.48	1.26	0.30	4.20	18	$3.00	$0.0397
76	0.35	0.27	2.04	46	2.04	2.04	1.73	0.39	4.43	18	$3.18	$0.0399
14	0.25	0.42	2.04	60	1.45	1.45	1.23	0.30	4.10	18	$2.95	$0.0400
2	0.25	0.67	1.8	60	1.39	1.39	1.18	0.30	3.94	18	$2.84	$0.0400
67	0.35	0.42	2.04	46	1.97	1.97	1.68	0.39	4.29	18	$3.13	$0.0406
5	0.25	0.67	2.04	60	1.39	1.39	1.18	0.30	3.94	18	$2.90	$0.0409
26	0.25	0.27	2.4	60	1.48	1.48	1.26	0.30	4.20	18	$3.09	$0.0409
79	0.35	0.27	2.4	46	2.04	2.04	1.73	0.39	4.43	18	$3.27	$0.0410
17	0.25	0.42	2.4	60	1.45	1.45	1.23	0.30	4.10	18	$3.04	$0.0412
46	0.3	0.27	1.8	46	1.76	1.76	1.50	0.39	3.83	18	$2.84	$0.0412
37	0.3	0.42	1.8	46	1.71	1.71	1.46	0.39	3.72	18	$2.79	$0.0416
70	0.35	0.42	2.4	46	1.97	1.97	1.68	0.39	4.29	18	$3.22	$0.0417
49	0.3	0.27	2.04	46	1.76	1.76	1.50	0.39	3.83	18	$2.90	$0.0421
8	0.25	0.67	2.4	60	1.39	1.39	1.18	0.30	3.94	18	$2.99	$0.0422
58	0.35	0.67	2.04	46	1.86	1.86	1.58	0.39	4.04	18	$3.08	$0.0423
40	0.3	0.42	2.04	46	1.71	1.71	1.46	0.39	3.72	18	$2.85	$0.0425
55	0.35	0.67	1.8	46	1.86	1.80	1.53	0.39	3.91	18	$3.02	$0.0429
28	0.3	0.67	1.8	46	1.63	1.63	1.39	0.39	3.55	18	$2.74	$0.0429
52	0.3	0.27	2.4	46	1.76	1.76	1.50	0.39	3.83	18	$2.99	$0.0434
61	0.35	0.67	2.4	46	1.86	1.86	1.58	0.39	4.04	18	$3.17	$0.0435
64	0.35	0.42	1.8	46	1.97	1.80	1.53	0.39	3.91	18	$3.07	$0.0436
43	0.3	0.42	2.4	46	1.71	1.71	1.46	0.39	3.72	18	$2.94	$0.0439
31	0.3	0.67	2.04	46	1.63	1.63	1.39	0.39	3.55	18	$2.80	$0.0439
73	0.35	0.27	1.8	46	2.04	1.80	1.53	0.39	3.91	18	$3.12	$0.0443
19	0.25	0.27	1.8	46	1.48	1.48	1.26	0.39	3.22	18	$2.57	$0.0444
10	0.25	0.42	1.8	46	1.45	1.45	1.23	0.39	3.14	18	$2.52	$0.0445
34	0.3	0.67	2.4	46	1.63	1.63	1.39	0.39	3.55	18	$2.89	$0.0453
22	0.25	0.27	2.04	46	1.48	1.48	1.26	0.39	3.22	18	$2.63	$0.0454
1	0.25	0.67	1.8	46	1.39	1.39	1.18	0.39	3.02	18	$2.47	$0.0454
13	0.25	0.42	2.04	46	1.45	1.45	1.23	0.39	3.14	18	$2.58	$0.0456
4	0.25	0.67	2.04	46	1.39	1.39	1.18	0.39	3.02	18	$2.53	$0.0465
25	0.25	0.27	2.4	46	1.48	1.48	1.26	0.39	3.22	18	$2.72	$0.0470
16	0.25	0.42	2.4	46	1.45	1.45	1.23	0.39	3.14	18	$2.67	$0.0472
7	0.25	0.67	2.4	46	1.39	1.39	1.18	0.39	3.02	18	$2.62	$0.0482

Additional graphs showing individual component performance vs. costs. For each component, 3 values were selected and entered into the optimization calculation.




Wire cost vs. diameter
Cost per 100 feet
$80
$70
$60
$50
$40
$30
$20
$10
$-
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Diameter of wire (mm)