

SES

Technical Research and Design Report



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Introduction

This document provides an overview of the light design research completed by the Stanford SES team in the spring of 2003 for the Light Up the World project. The team included 9 engineering and product design students who focused on developing an affordable LED based lighting solution for the developing world. This document includes a detailed analysis of options and decisions for each portion of the light, and presentation and discussion of initial and final prototypes.

Research Topics

Design Variables

Summary

Our design constraints are determined by the lifestyle of our users. As such, empathy plays a key role in determining the design of the product. Through observation and interaction with our users, we are able to understand their needs better; and through further interaction, we begin to iterate our design and evolve it into a complete solution.

Design Goals

Empathy - find out as much as we can about our users, their culture, their environment, and even their history in order to better understand their lighting needs.

Throughout the design process, we evolve our ideas by understanding the user experience. China, India, and Mexico, all have different cultures and different infrastructures. In order to understand the design possibilities, the team talked with anthropologists, specialists in international development, international students, and people within the target countries. The team sent shipments with light prototypes, cameras, and questionnaires to be distributed to target users, hoping to answer specific usage questions and to learn more about people's preferences.

Overview of Choices

The following table explores many of our design choices.

Table 1 - Design tradeoffs

Very poor, rural, off-grid	VS	Less poor, early adopters
Pros: this is in line with LUTW's vision of reaching out to the poorest of the poor to help replace their fuel-based lighting		Pros: slightly more affluent than the poorest of the poor; willing to take risks with new technology
Cons: it is difficult to create a sustainable business with them as our customer base		Cons: they may already be accustomed to incandescent lighting, which is brighter than current LED technology
Single-family households	VS	Entrepreneurs
Pros: volume would be higher, allowing for cheaper manufacturing costs		Pros: risk-takers are willing to invest in a new technology, with the promise of making more money from it
Cons: not all families will be able to afford the light		Cons: fewer risk-takers means lower

		volume, and higher price; people may not want to visit the local entrepreneur every day for battery recharges
One user	VS	Many users
Same as above		Same as above
For the home	VS	For the night market
Pros: greater number of homes than night markets Cons: light typically used for ambient setting, and the LEDs aren't designed as well for ambient lighting as incandescents are		Pros: Night market task lighting is perfect for LED's current technological limits. Plus, night markets are a great way to spread the word about the lights Cons: fewer night markets mean lower volume production
Task lighting	VS	Ambient lighting
Pros: LEDs provide even lighting with no abrupt patterns Cons: limited area of light		Pros: Small amount of energy required Cons: LEDs aren't designed for ambient lighting - the harsh light casts dark shadows, and isn't very warm
Hanging/portable light	VS	Stationary/sedentary light
Pros: Could potentially serve as both ambient and task lighting		Cons: doesn't take advantage of LED's size
High light output	VS	Low light output
Pros: bright lights give better light quality, optics improve usefulness of light Cons: higher price from higher quality components and added features		Pros: low power lighting requires less power generation and power storage so it is cheaper Cons: lower light levels

Decision Analysis

There are many variables to consider, and our task is made more difficult by the lack of easy access to each country.

Rural off-grid AND early adopters AND night market vendors – The China SES team chose to target both groups, as well as another group: night market vendors. The India team also chose to target both groups, and Mexico chose to target only rural off-grid users. We arrived at these decisions by talking with anthropologists and other international experts who understand the cultural mores of each country.

Single-family households (not entrepreneurs) – we will sell a greater number by targeting single-family households. Entrepreneurs will also be required to pay more money initially than would a single-family household. We also have had experts in the industry who have tried the latter model and failed.

Single-user (not multiple users) – for similar reasons as above, we would sell a higher volume by selling to single-users and thus bring the cost down of each light. Our expert advisors have also cautioned against setting up local entrepreneurship because of cultural or social inertia.

Ambient/task lighting – After much debate, prototyping, and personal exposure, we came to the conclusion that our light should be an ambient task light, or a tasking ambient light. That is, the result is a compromise between the two because the Luxeon star is bright enough to light up a large area (approx. 7' x 7'), but its light is weak enough not to function as a full ambient light (like a 40W incandescent bulb)

Hanging/portable light (not Stationary/Sedentary light) – We chose the hanging/portable light over a stationary light based on our observations in our respective countries. The target households in China use a variety of power sources—electricity, coal, biomass, kerosene and more—generally with low output lighting. Most of the target households in India use portable kerosene lamps. Most of the target households in Mexico use battery-powered flashlights. Since most households rely on only 1 or 2 small lights, it made sense to us to make small lights as well. These lights would be portable, so that people could move them around for different purposes.

High light output and low light output lights – because our target markets are different between countries and within countries, we are looking to design lights for a variety of income brackets, so we will design both high and low light output lights.

LED Technology

Summary

We chose a 1-Watt (1W) white LED, specifically the Luxeon Star, as the light source for our lamps. As our overall goal is to improve upon existing non-electrified (or unreliably electrified) lighting in the specific developing countries of China, India, and Mexico, we found the LED to be the best non-fuel-based compromise between two major light factors of a feasible solution: light output and power consumption.

Design Goals

The LED's attributes speak directly to the design goals of the light:

- Improved light output
- Low power requirements (battery or low solar wattage operable)
- Longevity
- Durability
- Reliability
- Portability
- Safety
- Cost-effectiveness
- Minimized complexity and components

Overview of Choices

Many combinations of lighting systems could provide a wide variety of useful light. We based our decisions, making tradeoffs and compromises based on the target users.

On one extreme of the spectrum of light sources are the existing fuel-based options (e.g. kerosene, wood, candle), which provide minimal light with adverse health and environmental consequences. On the other extreme are incandescent and compact fluorescent bulbs, whose desirable light output and quality are achieved at the cost of seldom-available high power sources. These light sources also often end up producing more heat than light.

LEDs fall somewhere in the middle of the spectrum, providing a decent amount of light with an extremely low power draw. Currently, the 1W LED we are using is the "best" LED commercially available, in terms of lumens/watt (light efficiency). Lower-wattage LEDs exist, but would require multiple bulbs to achieve the light output that the 1W LED provides. In addition, the increased number of bulbs would likewise increase the complexity of the lamp.

Another factor in our decision is that technology research is focused on increasing the light efficiencies of these higher-wattage LEDs. More light-efficient LEDs exist in prototype and are on the cusp of introduction into mainstream availability.

Comparison Matrices

Below are several comparisons of lighting options.

Table 2 - General light source comparison

	Candle	Kerosene Wick Lantern	Flashlight	40W Incandescent	Compact Flourescent	Nichia .1W LED	Luxeon 1W LED
Current (mA)	N/A	N/A	1000	350	125	20	350
Voltage (V)	N/A	N/A	6	120	120	3.4	3.5
Power (Watts)	N/A	N/A	3.6	40	15	0.1	1
Lumens	1	4	40	500	600	1.5	25
Efficiency (Lumens/Watt)	0.01	0.05	11	12.5	40	15	25
Cone angle (degree)	ambient	ambient	20	ambient	ambient	25-60	110
Color	orange	orange	warm yellow	warm yellow	warm yellow	bluish white	bluish white
Durability	M	M	H	L	L	H	H
Bulb life (hours)	2	4	3	1k	10k	100k	10k - 100k
Power Drain/Energy on grid	N/A	N/A	1.2 hours	30 kWh	150 kWh	60 hours	3.5 hours
Fixed Cost	\$0.25	\$0.10	\$1.00	\$1.00	\$5.00	\$0.16	\$2.78
Operating Cost (per 1000 hrs)	N/A	\$40.00	\$0.30	\$3.00	\$1.80	\$0.90	\$0.90

* Assuming cost of 9 cents per kWh

Figure 1 - Light and illuminance comparison, courtesy of Evan Mills, Lawrence Berkeley National Labs

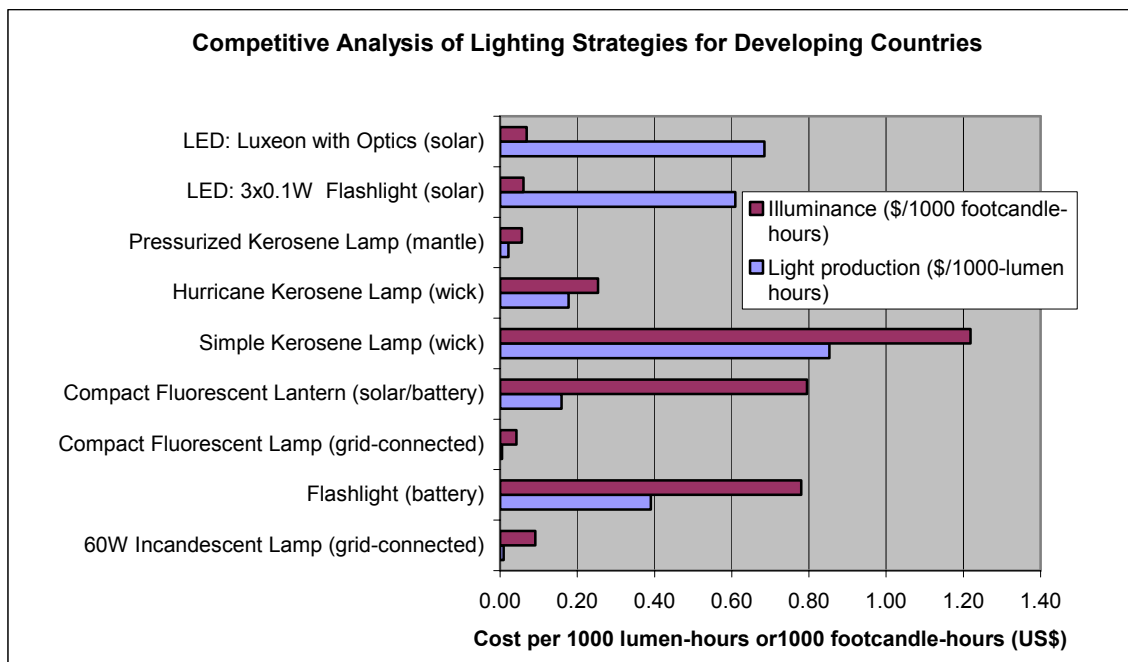


Figure 2 - First-cost comparison, courtesy of Evan Mills, Lawrence Berkeley National Labs

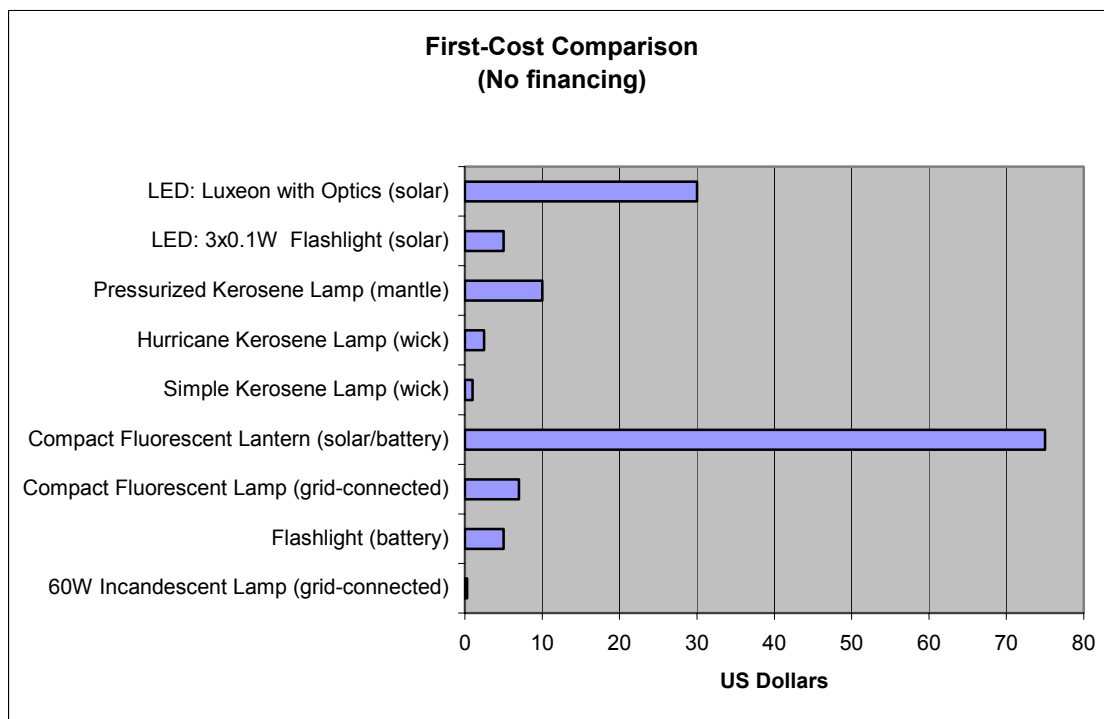


Table 3 - Light source comparison of CFL & Luxeon LED lamps over 50,000 hours, courtesy of Light Up the World

	Bulb (25W)	CFL (7W)	Luxeon (1W)	Kerosene wick
Lamp cost \$US	1	5	10	\$1
Lumens Output	250	250	40	10
Lamp life (hours)	1,000	6,000	50,000+	5,000
Lamp Lumen-hours per \$	250,000	300,000	200,000	50,000
Fuel cost*	1	1	1	0.25
Lamp consumption**	25	7	1	0.05
Lifetime energy***	1250	350	50	2500
Energy cost \$	1250	350	50	625
Total system cost (Lamp + Energy) \$	1300	392	60	635
System Lumen-hours per \$	9,615	31,888	33,333	787
Total system cost per lumen \$/lm	5.2	1.57	1.50	63.5

*\$/kWh for electric lamps, \$/L for kerosene. Since LUTW normally uses only Pico power systems all three of the electrically based lighting units were accorded the same fuel cost in order to make the comparisons realistic.

**Watts for electric lamps, L/hour for wick lamp.

***kWh for electric lamps, liters for kerosene.

Summary of CFL & Luxeon lamp comparison over 50,000 hours

1. CFL has a [6:1] advantage in total lumen output
2. system lumen-hr/\$ are virtually equal
3. total system costs/lumen are virtually equal
4. total system costs are [6:1] in favor of Luxeon
5. power supply for Luxeon smaller by a factor of [7:1]
6. Luxeon has at least a [8:1] lifetime advantage plus ruggedness
7. Luxeon has approximately a [4:1] optical efficiency advantage

Experiments

The recommended lighting levels for various tasks differ greatly from country to country. For example, in the United States and other first-world nations, the recommended levels for reading are approximately 100-200 foot-candles, whereas in China, reading is rated from only about 20-50 foot-candles. (One foot-candle is equal to one lumen per square foot; lux is the metric equivalent - one lumen per square meter).

Table 4 - Recommended lighting levels in foot-candles, from IAEEL*

Task	China	Mexico	USA
Desk	7-15	90	20-50
Reading	20-50	110	100-200
Retail Stores	7-15	20	20-50
Classrooms	7-15	40	20-50
Hospitals	5-20	6	10-20

*Data for India not available

The 1W LED light output, 25 lumens, fulfills the recommended lighting levels most effectively when focused into a small area. What does this number really correspond to? How does the quality of the light truly compare to a flame and an incandescent bulb?

In trying to gain empathy with our potential users and to understand the amount of lighting produced and what is actually required, we did a variety of simulations for qualitative evaluation.

One of the first experiments we did was to burn a kerosene lamp in a small, windowless room. Immediately, as the black smoke swirled about us, we were convinced that providing an alternative lighting source to kerosene would be greatly beneficial. (We were even using “Clean-burning, Low-odor” kerosene!)

We compared this light to existing LED and incandescent flashlights to get a benchmark on task versus ambient lighting. Afterwards, we wired up several Luxeon star bulbs and empirically evaluated various combinations and orientations, including those with and without optics and diffusers. We found that at close range (within several feet from the source) the 25 lumens provided by one single 1W LED bulb was indeed sufficient to read by, as well as to sit around a table and be able to have a visible conversation. The LED light was more of a task light, whose beam could be further focused. However, its cone angle of 105 degrees made its use as a smaller-area ambient light seem plausible.

After choosing the target users and determining the type of lighting needed (a mix of task and ambient), we simulated a night market in a windowless room, using only LED lighting. What we discovered was that one LED bulb provided enough “ambient” light for interactions across a table, be it for a vendor in a night market, or a family eating dinner.

Decision Analysis

For many reasons already mentioned, the LED is an attractive solution to eliminating the issues of current lighting in poor parts of the developing world. Some finer details are discussed here based on the data presented.

LEDs compared to other light sources - The biggest competitor to LEDs in terms of light efficiency are compact fluorescents (CFLs). Although CFLs are the most efficient bulbs today, they are not efficient at low power levels— CFLs of less than 5 watts end up being on par with an incandescents in efficiency, with much of their energy lost as heat. In countries such as Mexico where alternative power generation is not being pursued in conjunction with an LED light, the low power consumption of the LED light would serve to reduce the number of batteries used, correlating to a decrease in income expenditure on batteries, as well an improved environmental impact.

CFLs and incandescents are poor in the aspects of durability and portability, while the LED is the most versatile due to its size, durability, and portability. One main advantage that LEDs have over other light sources is that the LED is a point source whose light can be focused, so its light output is more effective. The combination of power consumption, cost, and durability, and useful light output all point towards the LED.

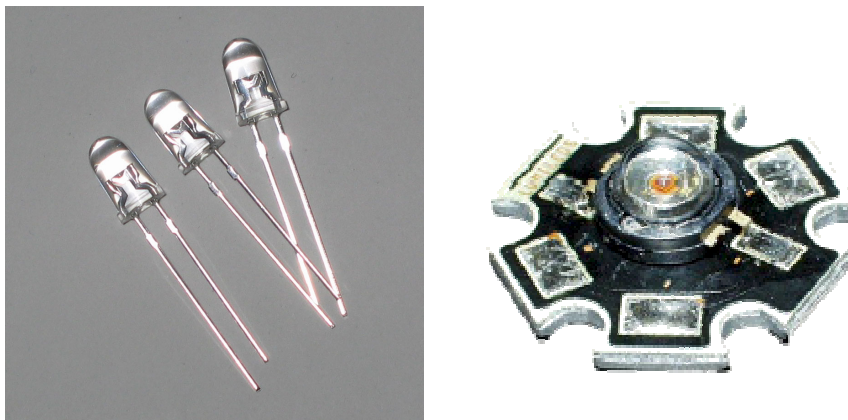


Figure 3 - .1W Nichia LEDs and 1W Luxeon Star LED

Type of LEDs – white LEDs are available with several different power ratings. We have chosen to stick with the .1W and 1W LEDs, shown above, because they are the most developed of the white LED choices. The following table compares .1W and 1W LEDs.

Table 5 - LED power comparison

Type	Power	Approximate light output	High volume price
Nichia	.1W	2 lumens	\$0.75
Luxeon Star	1W	30 lumens	\$2.78

The table shows that the 1W LED is more efficient (higher lumens/watt) and more cost-effective (higher lumens/dollar.) The benefit of using a .1W LED is that with a lower power rating, the requirements for power generation and power storage are reduced. Running the 1W LED at lower power can also reduce these demands.

Number of LEDs - Another major point of deliberation in the design process was the number of LEDs. From various field accounts, we were told that a 1W bulb is enough to read by. We corroborated this stance with our experiments, thus clinching our decision to use a single 1W LED.

Although LEDs cannot light up an entire room singly, several of them can be strung together to cover the entire room. From our testing, we found that 2 LEDs spread out from each other are more effective than 2 LEDs close to each other, and this helped us decide to incorporate only one 1W LED into each light design. One bulb keeps the cost of the light low and affordable, with the option of increasing buying more lights with increased income to increase light levels.

An example from David Irvine-Halliday supports this concept, from a power perspective:

“Assume that a 60 Watt [incandescent bulb] is used and it provides enough light for 12 children to read reasonably comfortably with. Energy wise this is a 20 times increase in energy requirements when compared to the three, 1 Watt, Luxeon SSL lamps which will be required. The use of a 30 Watt [Compact Fluorescent] would mean a 10 times increase in energy requirements.”

The LED technology enables many designs and approaches, and the driving factors behind the light designs are the target user's needs and their economic and lifestyle factors. The following is a summary of the benefits of LEDs:

- Low power consumption
- High light efficiency
- Ruggedness
- Reliability
- Longevity
- Bright future – technology increasing, costs decreasing
- Versatility
- Safety
- Portability
- Cost-effectiveness

Luxeon Star LEDs

While 1W LED bulbs are available from several companies, the team has decided to focus on the Lumileds Luxeon Star for a few reasons. Lumileds is the current leader in lumens/watt for 1W LEDs, and the Luxeon Star package—which consists of an emitter attached to a metal heat sink—has a reputation for reliability. In addition, LUTW already has a good relationship with Lumileds.

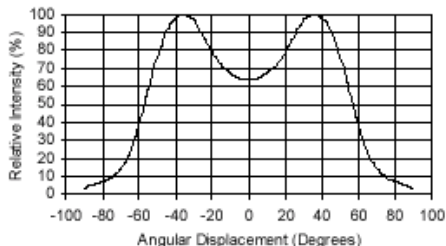
Some basic information regarding the Lumileds Luxeon Star 1W LED follows.

Table 6 - Luxeon Star general information

Light output	30.6 to 39.8 lumens
Optimum Current	350 mA
Forward voltage	3.03 to 3.51 V

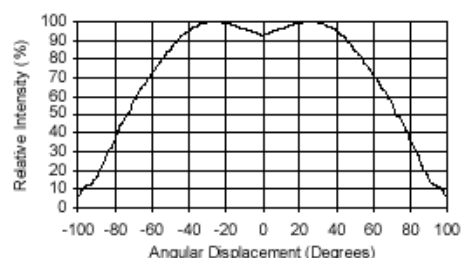
Lumileds offers three types of Luxeons, each with a different light emission pattern: Batwing, Lambertian, and Side-emitting. The Batwing and Lambertian varieties work best with lenses, and the Side-emitting one works best with a parabolic reflector. As seen from the emission graphs, the Batwing bulb is conducive to a more ambient effect whereas the Lambertian is more suited to a focused, task-oriented light. The Luxeon is available as an emitter-only, mounted on a heat sink, or mounted on a heat sink with a collimator. Using the emitter only increases complexity in the manufacturing process. The following plots show emission patterns of the different LED types.

Batwing Radiation Pattern (without optics)



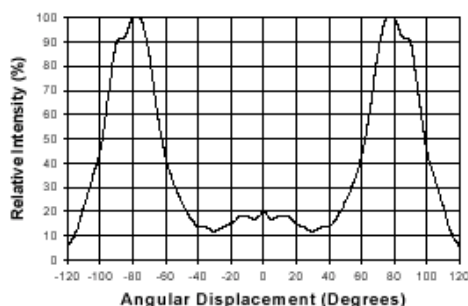
Typical Representative Spatial
Radiation Pattern for Luxeon Star
White.

Lambertian Radiation Pattern (without optics)



Typical Representative Spatial
Radiation Pattern for Luxeon Star
Red, Red-Orange and Amber.

Side Emitting Radiation Pattern (without optics)



Typical Representative Spatial
Radiation Pattern for Luxeon Star
Red, Red-Orange and Amber

Figure 4 - Spatial radiation patterns for Luxeon Star models, courtesy of Lumileds

Pricing and Sourcing Info

The following is a table on the quantity pricing of the Luxeon Star. The price shown for the Batwing is the same for the Lambertian and Side-emitting diodes. We are assuming the highest volume price, \$2.78, for our cost calculations.

Table 7 - Luxeon Star pricing, courtesy of Lumileds

Lumileds PN	Description	0-1k	10k	100k	>500k
LXHL-BW01	1W, White, Batwing, Emitter	\$6.42	\$4.62	\$3.51	\$2.67
LXHL-MW1C	1W, White, Batwing, Star	\$6.67	\$4.80	\$3.67	\$2.78

As mentioned earlier, LED technology is rapidly increasing, and thus, a more efficient LED may be included in any subsequent prototyping. For example, Lumileds will be offering a higher-lumen 1W bulb, a 3W 50-lumen bulb and a 5W 100-lumen bulb in the near future. Although the 2W and higher power LEDs are currently too expensive for the LUTW lights, they are valuable benchmarks for the future; development of higher-watt LEDs will likely drive down the price of the 1W LEDs we are working with.

Power Generation

Summary

Human power and solar power both provide viable options for power generation; we have chosen to focus on solar power because it is available in sizes appropriate for single families. For a low-power application, our batteries require a relatively high charging voltage. An optimal low-cost solution is to use a number of low-voltage cells in series to increase the overall voltage. The desired current output can be achieved by choosing cells of a large enough size and high enough efficiency.

Design Goals

- On or off the electric grid
- Reliable and durable
- Low-cost
- Low-maintenance
- Simple, reliable interface with light

Overview of Choices

The following power generation choices were examined: solar power, human power, wind power, and hydroelectric power. Wind and hydroelectric were discarded as a result of high unit cost and high maintenance cost. While these power sources offer much potential, our research indicates that these systems become viable at a larger scale (several villages) than our target of a family end-user.

Human power generators involve a pedal or hand crank to turn the shaft of a generator. This option may be a viable option for a village-scale entrepreneurial model. In this scenario, a shopkeeper owns the pedal generator and charges a fee for each battery recharge. The price of a pedal power system would require significant investment and thus we see it as an unattractive option for the typical rural family.

Solar power has the obvious disadvantage of environmental constraints on charging time. In addition, the technology is sufficiently complex that a problem with the system would likely require full replacement of the panel. Nevertheless, solar power is a familiar technology in many rural regions and it is relatively simple to employ. In addition, solar power can be scaled to precisely fit the power needs of a given device. An overview of some of the key issues regarding human power and solar power is provided below.

Table 8 - Human/solar power comparison

	HUMAN		SOLAR	
	Pro	Con	Pro	Con
User friendliness	<ul style="list-style-type: none"> • Bicycles are familiar and culturally accepted • Governments support the technology (e.g. India) 	<ul style="list-style-type: none"> • Need energy and time to charge—hard if tired from other work. • Pedaler needs more calories in diet to produce energy 	<ul style="list-style-type: none"> • Solar panels are familiar to some • Governments support the technology (e.g. India) • No activity needed to charge batts 	<ul style="list-style-type: none"> • Many failed solar projects in the past; may have left bad impressions

Location and availability	<ul style="list-style-type: none"> • Available 24 hours a day, indoors or outdoors 	<ul style="list-style-type: none"> • Need indoor space for use and/or nighttime storage 		<ul style="list-style-type: none"> • Available daylight hours only; dependent on weather and climate (clouds→ up to -90%) • Must be in sunny location (could be difficult in forests/crowded cities) • Need to bring inside at night to avoid theft
Maintenance and reliability	<ul style="list-style-type: none"> • Mechanical parts can be repaired locally 	<ul style="list-style-type: none"> • Many moving parts increase chance of mechanical failure • Generator can't be repaired locally • Dirt in mechanisms and wear in gears decrease efficiency 	<ul style="list-style-type: none"> • No moving parts, few parts to break 	<ul style="list-style-type: none"> • Can't be repaired locally • Degradation of amorphous silica reduces power by up to 20% after a year (depending on PV type)¹ • Dust and dirt decrease power output by up to 7%² • High temperatures reduce power output by up to 12%²
Cost vs. power	\$30/150W (no bike), limited availability of low-watt systems		Approx. \$2.50 per Watt → \$7.50/3W, \$375/150W	
Business models	<ul style="list-style-type: none"> • Good for entrepreneur model, communal model • Produces job for active pedaler 	<ul style="list-style-type: none"> • Too expensive for family model 	<ul style="list-style-type: none"> • Good for entrepreneurial model, communal model, family model • Produces job with no fitness requirements 	

Decision Analysis

Given the scale of the power demands and our usage scenarios, the team has chosen to use solar power. Amorphous silicon panels offer durability at the expense of efficiency, while single-

¹ Degradation Analysis Of Silicon Photovoltaic Modules,
<http://www.promes.ch/bulletins/PN32/16PVSEC/VC305.pdf>

² How much electricity will PV produce?
http://www.sdenergy.org/pvweb/production_homes.htm

crystalline panels offer higher efficiency and have been on the market for a much longer period of time. Though single-crystalline panels can be fragile, epoxy resin mounting causes cells to become durable and robust.

In the case of powering the light utilizing grid electricity, an additional AC/DC converter will need to be purchased. The converter jack plugs directly into the lighting unit and can power the light but not recharge the batteries. For off-grid power generation, the primary function of the power source is to recharge the batteries which power the light at night. It is therefore critical that the mechanism for recharging is robust, reliable, and relatively low-maintenance.

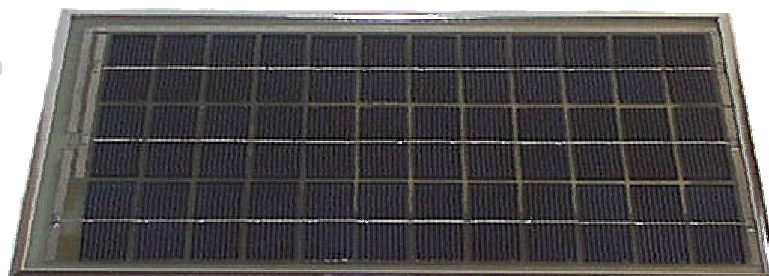


Figure 5 - Array of PV cells

PV Sizing

Given two 1800 mAh NiMH batteries that can be discharged to 80%, the total available milliamp hours (mAh) is 2880. Using the 1.2W solar panel, the batteries can be recharged in 7.2 hours of direct sun. In order to meet voltage and current requirements for the solar panel, we need to use several small PV panels in series, with the number of cells controlling the panel voltage and the size of the cells controlling the output current. The following table shows how to size PV panels, using specs from Jia Wei Solar China Lts. in Hong Kong.

Table 9 - PV sizing guidelines

Symbol	Meaning of symbol	Our value	Unit of measurement	Explanation
<i>LED circuit</i>				
V_{LED}	forward voltage across LED	3.70	volts [V]	for Luxeon Star
V_{ALL}	forward voltage across all components in circuit	3.80	volts [V]	approximate for entire circuit—LED, MOSFET, etc.
$E_{CIRCUIT}$	efficiency of circuit	0.90		for PIC step-up and step-down circuits
$V_{CIRCUIT}$	forward voltage used by circuit	4.22	volts [V]	$V_{CIRCUIT} = V_{ALL}/E_{CIRCUIT}$
I_{LED}	current through LED	350	milliamps [mA]	for Luxeon Star
$I_{CIRCUIT}$	current through circuit	400	milliamps [mA]	approximate for entire circuit—LED, PIC, etc.
<i>Batteries</i>				
N_{BATT}	number of batteries	2		tradeoff between low cost and high power output; we recommend 2-4 AAs
A_{BATT}	mAh of each battery	1800	milliamp-hours [mAh]	for good-quality battery
$F_{USEABLE}$	usable fraction of mAh	0.8		tradeoff between factors—high fraction causes over-draining so

$A_{USEABLE}$	mAh available	2880	milliamp-hours [mAh]	reduces battery life, low fraction means less output from each battery $A_{USEABLE} = N * A_{BATT} * F_{USEABLE}$
V_{BATT}	battery voltage available	2.4	volts [V]	$V_{BATT} = 1.2 * N_{BATT}$ for AA cells
I_{BATT}	current used by circuit	704	milliamps [mA]	$I_{BATT} = V_{CIRCUIT} * I_{CIRCUIT} / V_{BATT}$
$I_{BATT,C}$	current used by circuit, in units of C	0.391	Cs [1/h]	$I_{BATT,C} = I_{BATT} / A_{BATT}$
$T_{CIRCUIT}$	time LED circuit can be used per recharge cycle	4.09	hours [h]	$T_{USEABLE} = I_{BATT} / A_{USEABLE}$
PV panel				
V_{CELL}	voltage per PV cell	0.48	volts [V]	for PV cells sourced through Jia Wei
V_{PANEL}	Required PV voltage	3	volts [V]	$V_{PANEL} = 1.5 * N_{BATT}$
N_{CELL}	number of PV cells	6		$N_{CELL} = V_{PANEL} / V_{CELL}$ (rounded to nearest cell)
I_{PANEL}	required PV current	400	milliamps [mA]	$I_{PV} = I_{CIRCUIT}$
I_{perA}	current per unit area of PV cell	35	[mA/cm ²]	for PV cells sourced through Jia Wei
A_{CELL}	total PV cell area	11.4	square centimeters [cm ²]	$A_{CELL} = I_{CIRCUIT} / I_{perA}$
W_{CELL}	PV cell width	5.3	centimeters [cm]	for PV cells sourced through Jia Wei
W_{PANEL}	panel width	10.6	centimeters [cm]	$W_{PANEL} = 2 * W_{CELL}$
W_{MARGIN}	margin for width	0.9	centimeters [cm]	safety factor
W_{TOTAL}	total width	11.5	centimeters [cm]	$W_{TOTAL} = W_{PANEL} + W_{MARGIN}$
H_{CELL}	PV cell height	2.16	centimeters [cm]	$H_{CELL} = A_{CELL} / W_{CELL}$
H_{PANEL}	panel height	6.47	centimeters [cm]	$H_{PANEL} = 3 * H_{CELL}$
H_{MARGIN}	margin for height	0.97	centimeters [cm]	safety factor
H_{CORNER}	corner compensation	0.57	centimeters [cm]	$H_{CORNER} = 1 / W_{CELL} * 3$
H_{TOTAL}	total height	8.01	centimeters [cm]	$H_{TOTAL} = H_{PANEL} + H_{MARGIN} + H_{CORNER}$

Pricing and Sourcing Info

The preferred solar panel solution uses an array of series wired silicon solar cells, encased in conformal epoxy resin and mounted on a rigid substrate. LUTW can generally obtain better prices from companies already set up to produce low-power solar panels, such as those used in garden lights. Because each solar cell is small, manufacturers can reduce costs by obtaining small pieces from other manufacturing processes or from partially damaged cells, and refurbishing these cells into smaller arrays for low power applications. A company with the capability to produce these panels is Jia Wei Solar, based in Hong Kong. The following table shows pricing of solar panels, with an estimated price of \$2.50/watt.

Table 10 – Estimated solar panel pricing, in volumes of 100,000s

Component	Quantity expected	Cost
1.2 Watt PV, silicon cell module with conformal coating	1	\$3.00
0.6 Watt PV, silicon cell module with conformal coating	1	\$1.50

Power Storage

Summary

For target markets in China and India, AA Nickel Metal Hydride (NiMH) batteries are specified in the design due to their high energy density and long cycle life. NiMHs are not environmentally toxic, a disadvantage inherent to many of their counterparts (Alkaline, Nickel Cadmium, and Lead Acid). Due to recent technological advances, NiMHs are comparable in cost per amp/hour when compared to other alternatives. AA batteries are chosen because they are the most rapidly advancing NiMH battery package, and because their small size allows for flexibility in the industrial design.

D cell alkaline batteries are specified for customers in Mexico. The Mexico light uses non-rechargeable batteries because it has no power generation; it uses D cells because they are already widely available in Mexico, and are standard in a number of products there. One-use D Cells also have a higher current/hour output than their AA counterparts, giving designers more flexibility.

Design Goals

Power storage requirements for our target users in China and India are as follows.

- Affordable, rechargeable solution
- Ample power to drive single Luxeon 1W LED for 5 hours
- Able to be recharged within one day
- Compact size

The requirements are very similar for users in Mexico, however the ability to recharge and the size of the battery were not necessary drivers.

Overview of Choices

We analyzed choices including the standard lead-acid batteries found in cars and disposable and reusable alkaline batteries. We also examined options for nickel cadmium and nickel metal hydride technology and lithium ion batteries, as found in common portable electronic devices. Our analysis also included evaluation of supercapacitor technologies. The options are summarized as follows:

Nickel-cadmium - mature but has moderate energy density. Nickel-cadmium (NiCad) is used where long life, high discharge rate and extended temperature range is important. Main applications are two-way radios, biomedical equipment and power tools. Nickel-cadmium contains toxic metals.

Nickel-metal-hydride - has a higher energy density compared to Nickel-cadmium at the expense of slightly reduced cycle life. There are no toxic metals. Current applications include mobile phones and laptop computers.

Lead-acid - most economical for larger power applications where weight is of little concern. Lead-acid is the preferred choice for hospital equipment, wheelchairs, and emergency lighting and UPS systems.

Lithium-ion - fastest growing battery system; offers high-energy density and low weight. Protection circuit are needed to limit voltage and current for safety reasons. Applications include notebook computers and cell phones.

Reusable Alkaline - Its limited cycle life and low load current is compensated by long shelf life, making this battery ideal for portable entertainment devices and flashlights.

Supercapacitor - Energy storage is by means of static charge rather than of an electro-chemical process that is inherent to the battery.

Comparison Matrix

Table 11 - Rechargeable battery comparison

Chemistry	Manufacturer	Type	Nominal Voltage	Nominal Capacity Amp-hrs	Nominal Capacity Watt-hrs	Usable Cycles	Watt-hr/kg	Watt-hr/liter
Li-Ion	BYD	AA	3.6	0.75	2.7	600+	135	365
NiCad	BYD	AA	1.2	0.9	1.08	800+	47	142
NiMH	Gold Peak	AA	1.2	1.6	1.9	600+	72	259
Rechargeable Alkaline	Rayovac	AA	1.4 to 0.9	1.6	2.24	100+	80	220
Lead Acid	B&B	Box	12	12	144	350+(1)	36	103
Supercapacitor	Powercache	Box	2.3	100 F	0.15	200,000+		4.1
Supercapacitor	Powercache	Box	2.3	2500 F	3.7	200,000+		6

Figure 6 - AA NiMH and D Alkaline batteries



Decision Analysis

For the Asian market, NiMH batteries feature a high energy density, a long cycle life, and a relatively low cost, without being toxic to the environment. On the downside, distribution channels must be developed and a circuit must monitor battery charge so that users can be forewarned as charge depletes.

Other rechargeable battery options had the following significant downsides:

- *Nickel-cadmium* - mature but has moderate energy density, high toxicity.
- *Lead-acid* - Benefits from deep cycle, but too large for single-family application.
- *Lithium-ion* - High density, low weight, but needs protection circuitry. High cost.
- *Reusable Alkaline* - Limited cycle life and low current. Not rechargeable. High cost over time.
- *Supercapacitor* - Promising future, but currently high cost and low availability.

While AA NiMHs are the best match for our target users in Asia, D cell Alkaline batteries are a better alternative for the Mexican market given their need for a non-rechargeable solution to minimize upfront system cost.

Driver Circuit

Summary

Of the circuitry options we've explored, a circuit built with a microprocessor gives the best functionality and flexibility. With a PIC microprocessor circuit, we can control current through the LED, automatically shut off the battery to prevent over-discharge, and provide a user interface for the light.

Design Goals

- Control current through LED
- Prevent deep battery discharge
- Produce at low cost
- Design for energy efficiency
- Design with few components

Overview of Choices

To control the current in the LED, the driver circuit can use hardware current control (including analog control with op-amps or digital control with a switching regulator chip) or firmware current control (microprocessors with custom code.) Battery shutoff can be implemented through additional circuitry or through firmware.

Comparison Matrix

Table 12 - Driver circuit comparison

Circuitry Options	Pro	Con
Hardware current control		
Op-amp circuit (current LUTW solution)	<ul style="list-style-type: none"> • Simple to design 	<ul style="list-style-type: none"> • Many components • No automatic battery shutoff
IC switcher (e.g. LM3478 – high efficiency switching regulator controller)	<ul style="list-style-type: none"> • Simple to design • Few components • ~\$1.20 for all components except LED with LM3478 • Energy efficient 	<ul style="list-style-type: none"> • No automatic battery shutoff
Firmware current control		
PIC driving a switching regulator	<ul style="list-style-type: none"> • Few components • \$.80 for all components except LED • 90% energy efficient • Automatic battery shutoff • Extra functionality at no additional cost, since we've already invested in a PIC (e.g. low battery warning, dimming) • Flexibility in number of batteries used • PIC can also be used as charge controller for PV 	<ul style="list-style-type: none"> • Possible patent issues with shared code

Decision Analysis

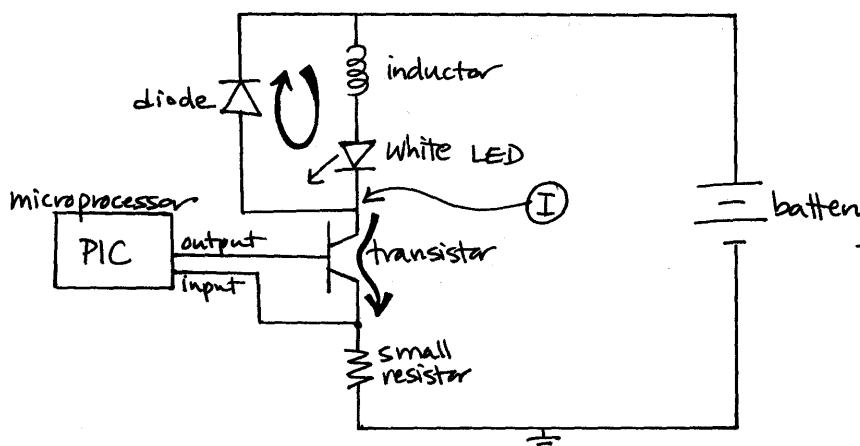
The team has chosen to design circuits with PIC microprocessors. This is the least expensive of the proposed solutions. It is ideal because the same small set of components can achieve current regulation for the LED, automatic battery shutoff, and PV charge control. Using a microprocessor gives us flexibility for creating a user interface. The PIC also enables us to change the circuit's functionality without changing the hardware, so that if a new LED has different current requirements, we can update the firmware without changing the rest of the circuit design.

PIC Circuit Functionality

The PIC circuit enables four main functions.

1. *Current control* - The goal is to keep the current through white LED constant. Figure 1, below, shows a conceptual diagram of a PIC circuit in step-down configuration. The PIC output turns a transistor on and off. If the transistor is on, current flows through it and the current through the LED increases. If the transistor is off, current flows around the loop and the current through the LED decreases. The PIC can sense current by reading the voltage from the small resistor on its input line, and it uses this information to time the switching, so that current rises and falls around the ideal current value, which is 350mA for a Luxeon Star.

Figure 7 - Sketch of PIC switching regulator circuit



2. *Battery control* - NiMH batteries are sensitive to deep discharge. To protect the batteries from over-draining, the PIC can turn off the LED at the appropriate battery level—around .8V for NiMH AAs. One way to sense this voltage is to measure the batteries directly, using a voltage divider feeding into an analog input on the PIC. Another way is to monitor the state of the transistor output, since the percentage of time that the transistor is on is proportional to the battery voltage. When the battery gets low enough that the transistor must be on all the time, the PIC can turn the LED off, or wait a specific amount of time before doing so.

For certain configurations, battery shutoff takes care of itself. When the battery voltage is no longer higher than the forward voltage of the LED and other components, current stops flowing. Forward voltage is around 3.4V for a Luxeon Star, so with a 4-battery configuration the current will stop flowing on its own at around .85V ($=3.4V / 4$), above our threshold voltage.

Depending on the circuit, the PIC can be used for step-up or step-down configurations. With 4 AA batteries and a Luxeon LED, there is more than enough voltage to turn the LED on, so we can use a step-down configuration to control the current (as explained above.) With 2 AA batteries and one Luxeon LED, the batteries do not provide enough voltage to turn the LED on. A step-up circuit uses an inductor to charge a capacitor, so that the voltage for the LED is higher than the actual battery voltage.

3. *Charge control* – The PIC can be used as a controller for charging with a PV. If we're charging NiMH AA batteries, it is important to monitor the voltage of the batteries and to avoid over-charging them. The PIC can read the battery voltage and automatically shut off the charging when they have reached their ideal voltage. Current control is not necessary when charging with PV cells in our size range, because the current will never exceed the NiMH limits.
4. *User interface* – We can adjust the brightness of the LED by changing the current through it. This is helpful for the user interface, because it allows us to flash the light on and off to warn of low battery, to run the circuit at half-power for the last minutes before battery shut-off, and to use the push-button on/off switch as a dimming switch as well.

Pricing and Sourcing Info

The following table shows the main components of a step-down circuit. The exact bill of materials is dependent on the final circuit design.

Table 13 - Driver circuit components and pricing

Component	Quantity expected	Cost
Luxeon Star	1	\$2.78
PIC 12F629, pre-programmed	1	\$0.45
Inductor	1	\$0.08
BJT transistor	1	\$0.06
Shottkey diode	1	\$0.03
Switch	1	\$0.03
PCB	1	\$0.20
Total		\$3.63

Optics

Summary

The 25-40 lumens generated by the Luxeon 1W LED provide up to 55 Lux of incident light. The accepted minimum amount of incident light needed for performing basic tasks is 50 Lux. With this in mind, the tech team recommends incorporating optical elements to maximize the effectiveness of the modest amount we are generating. Lens, diffusion material, and reflectors can be used to transform the following key characteristics of incident light:

Angle – Also referred to as the cone, controlling the angle controls the area an incident beam covers. Task lighting is focused into a narrow cone with lens. Ambient lighting is dispersed widely with diffusion material.

Color – The color and tone of the light can be altered to a desirable quality with filters and gels.

Pattern – The light falling on and illuminating object can be altered to create even distribution or a reflective pattern.

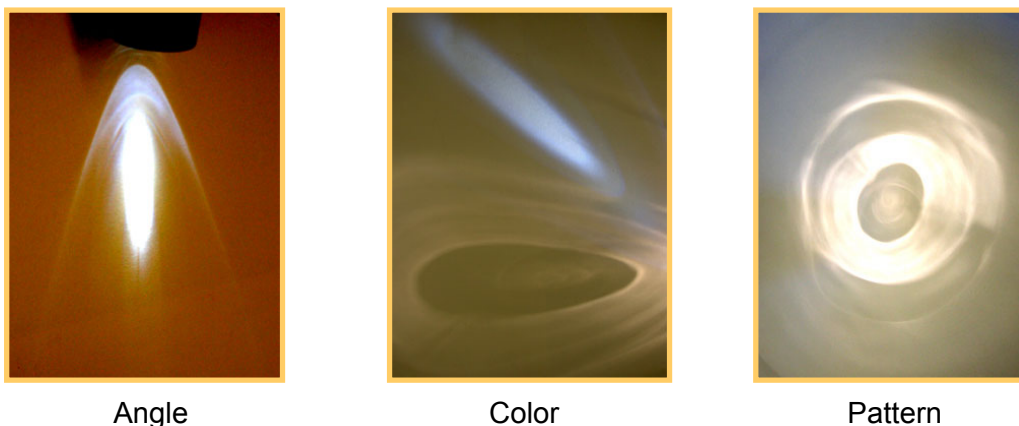


Figure 8 - Characteristics of incident light

Key concerns

Discomfort glare - Light sources of excessive brightness or uneven distribution in the field of view can cause glare of varying degrees from a mild sensation of discomfort to outright pain. Current LEDs have a high risk of discomfort glare due to the amount of light emitted from such a small surface area. The Luxeon 1W LED generates 25-40 lumens from a lamp with approximately 7mm² of surface area; looking straight into a Luxeon LED leaves bright spots on your eye. LED technology is advancing at such a pace that 120 lumens will be achievable in the next 5 years. Discomfort glare will be an important, if not the most important usability issue in LED lighting.

Amount of light – The 25-40 lumens generated by the Luxeon 1W LED will provide up to 55 Lux of incident light. The accepted minimum amount of incident light needed for performing basic tasks is 50 Lux. The tech team found it possible, although not desirable, to read and perform basic tasks with a 12 Lux light source. Making the most of the little amount of light a Luxeon 1W LED generates will be critical to the near term success of the final product. Future LED technology will offer more light.

Below is a chart of how current light sources compare in terms of light output.

Table 14 - Light output comparison

	Candle	Kerosene	12w optics	12w no optics	25w	40w	60w	CFL	White LED	Luxeon optics	Luxeon no optics
Illuminance (lux)											
1ft	4	7	6500	45	97	340	490	1300	148	1650	55
2ft	3	4	1600	20	53	152	202	322	38	420	17
4ft	3	3	384	10	23	52	72	102	13	113	7
8ft	3	3	10	5	10	21	28	38	5	33	4
Cone Diameter (in)											
1ft	Amb	Amb	3, 48	Amb	Amb	Amb	Amb	Amb	10	10	24
2ft	Amb	Amb	5, 74	Amb	Amb	Amb	Amb	Amb	16	16	66
4ft	Amb	Amb	10, 144	Amb	Amb	Amb	Amb	Amb	26	26	Amb
8ft	Amb	Amb	21, Amb	Amb	Amb	Amb	Amb	Amb	54	54	Amb
Minimum Lux needed for reading: 12											

Task v. Ambient – This was and is a key issue that drives optics and many other features of the final product – battery storage, housing, portability, and more.

Light quality – Quality of light is governed largely by color and distribution. Vendors selling food items at a night market needs a light source that will properly display the quality of their goods. Families need to be around a light that will enable social interaction. Evenly distributed and appropriately colored light are factors that will enable this.

Our Direction

Our final designs benefit from the basic characteristics of LEDs. The 105-degree cone in which they emit light provides the perfect ambient source without need for further optics. The Luxeon 1W LED also emits light very evenly throughout the cone. Still, there were some features we added to address the concerns listed above.

Rotating Lens

For each country, the light will be primarily used as an indoor ambient lighting source, but to accommodate anyone who needs light, focused task light capabilities have been considered.

An idea employed in one of our final prototypes is that of a rotating lense. This lens can offer many lighting options to the user, with different optics at each of the positions for the rotating disc. Different optics could include a focusing lens for focused task light, a diffusion filter to cut down discomfort glare, a clear sheet to get as much ambient light as possible. The clear sheet would be made from a non-yellowing acrylic to protect against extended outdoor exposure, and coated with a non-refractive film so light is not lost as it passes through the lens.

There are many options for optics and diffusers to add to the rotating lens. One option is a standard focusing lens, much like a magnifying glass; the Lumileds LED collimator is an example of the focusing lens. A Fresnel lens offers the same functionality in a flat surface and a reflective surface that redirects side-emitting light forward—too expensive or inappropriate for

LED technology, respectively. A diffusion filter can be made from a piece of bead blasted acrylic sheet. Several other diffusion options are available, including prismatic sheet, louvers, reflective cones, mylar, and photographic gels. All were tested and some were found to be more efficient in light transmission.

Color

The Luxeon 1W LED emits a blue-green tint. 'Warming up' the light is a subtractive process that would involve knocking out a significant amount of light (about 20%) with color gels. While light quality is important, we do not believe we are able to sacrifice any light we are able to generate with the current 1W LED. No color correction features are included at this time. As LED technology continues to develop and generate more light per watt, color will increasingly become a priority.

Housing

Summary

The design of the housing will be driven by a large number of tradeoffs of function vs. manufacturing costs. For example, having a waterproof housing would be very desirable, but o-rings and seals would increase the cost. The housing could be designed with snap fits to hold the different components together in order to reduce the number of fasteners used and decrease assembly costs, but the consequence is the cost of more complex tooling. Adjustable optics make a more versatile light, but mean more parts and increased cost. A versatile clamping or mounting system would be great, but again this means increased costs.

Design Goals

The housing should meet the following criteria:

- Inexpensive – meets specifications of business plan
- Rugged – 6 foot drop test, weather resistant
- Long lasting – should survive at least 2 years of normal use without maintenance
- Safe – no pinch points or shock hazards, environmentally safe

Housing design considerations

Heat sink - Expert advice has informed us that the life of the 1W and greater LEDs we are proposing to use can be greatly increased if the emitter is used in conjunction with some type of heat sink to disperse the heat that would otherwise cause it to fail prematurely. This can be as simple as mounting the LED to a small piece of sheet metal, the actual dimensions of which remain to be determined.

Connectors - Several of our proposed designs call for the batteries to be recharged within the lighting unit, as opposed to in an external charger. This would mean that a connector of some sort would be used to connect the batteries to an external power source, if the power source is a separate unit. Information from field tests of similar projects tells us that this connector would be a likely failure point for the light. The connector should be durable, protected from dirt, the elements, and damage from a fall, and should be able to hold up to many cycles of use.

Battery access - since even rechargeable batteries have finite life spans, the batteries will need to be easily accessible by the user. In the case of a light that uses non-rechargeable batteries, the fatigue of repeated cycles of opening and closing will need to be taken into account to prevent failure.

Maintenance - The light should be designed for disassembly to allow easy maintenance by the user or by a trained service person. Screw captures prevent screws from falling out easily, while adhesives, heat stakes, and other irreversible fastening methods should be used judiciously.

Durability - It is likely that the lights will be used in rugged conditions. A crucial selling point will also be that the light will last a long time. The case and all internal components should be very durable, including switches, electronics, the emitter, solar cells, and battery doors. The unit should be able to survive at least a six-foot drop test.

Upgradability - Since this project seeks to take advantage of new and rapidly advancing technologies, it is likely that in a short time, better lights will be possible. Since the users will be investing a large amount of money, it would be useful to design in a degree of upgradeability.

For example, when brighter LEDs become available, perhaps the old one could be easily exchanged without necessitating the purchase of an entirely new light.

End-of-life - The end of the useful life of the product should be taken into account when choosing materials and manufacturing methods. Since the lights may not be disposed of properly, the use of chemicals that might be harmful to the local environment should be thought through. We do not want to cause long-term harm to the people we are trying to help.

Overview of Choices

Processes - The manufacturing processes available generally vary with tooling costs, increasing with part complexity. For example, the tooling for a pressure formed plastic part is inexpensive, but the parts can not have the detail and complexity of an injection molded part. A balance will need to be found with increased initial investment in tooling that yields decreased long term costs in the form of assembly costs and part count.

Some of the possible manufacturing process, listed in order of increasing tooling and increasing complexity possible:

- Pressure forming
- Rotational molding
- Extrusion
- Sheet metal stamping
- Injection molding

Materials - The following materials are well-suited for our project:

- *Thermoplastics* – inexpensive material, production costs vary.
- *Steel* – inexpensive, durable, but heavy. Must be painted or plated to resist corrosion.
- *Aluminum* – more expensive, but relatively lightweight. Does not necessarily need a finish.

Finishes - Some possible finishes that could be considered for metal parts include anodizing, plating and painting. The finishes can increase the durability and corrosion resistance of metal parts. The downsides are that many of them have undesirable environmental effects due to the acids and solvents involved, they constitute an additional step in production, and they add to the final cost of the parts.

Existing materials - It is possible to use existing parts or materials already in production to take advantage of economies of scale from other products. An example of this is the light currently distributed by LUTW, made from an end cap used in plumbing. The negatives of this are that the design of the light is very limited, and joining the different parts can be challenging if they were not intended to be used together.

Manufacturing

Summary

For high volume manufacturing, injection molded plastics are the most economical solution. Injection molding is appropriate for the light's housing, and for optics.

Design Goals

- Minimize number of components
- Minimize product cost
- Minimize tooling cost
- Minimize labor
- Minimize time to market

Overview of Choices

There are a number of manufacturing choices to be considered. To make the correct choice, material type, component size and geometry, part quality (tolerances and surface finish), production quantity, tooling cost, and production cost must all be taken into consideration. Given that the two materials that are under consideration are polymers and metals, the following comparison matrix compares common molding, extrusion and forming processes.

Comparison Matrix

Table 15 - Manufacturing methods comparison

Manufacturing Options	Pro	Con	Other Considerations
Polymers			
Injection Molding (economical for >10,000 units)	<ul style="list-style-type: none"> • High production rate (~10-60 second cycle time) • Little material wasted • Low labor requirement • Finishing costs low • Good for high precision and complex parts 	<ul style="list-style-type: none"> • Requires complex dies – high tooling costs • Lead time can be several weeks to account for creating die • Moderate to high equipment costs • Low flexibility due to dedicated molds, die changeover and machine set-up times 	<ul style="list-style-type: none"> • Best for high-precision, complex parts • Maintain generous radii • Maintain uniform thickness • Threads possible • Pay attention to parting line and direction of draw • Draft angles • Min section ~ 0.4mm • Max section ~ 13mm
Blow Molding (suitable for 1000-10,000,000 units)	<ul style="list-style-type: none"> • Lead time typically a few days • Generally little material wasted • Short set up and change-over times • Low labor • Finishing costs low (only trimming) • Good surface detail 	<ul style="list-style-type: none"> • Low production rate (100-2500 pieces/hr) • Low flexibility due to dedicated molds • Moderate to high tooling costs • Moderate to high equipment costs • Poor control of wall thickness 	<ul style="list-style-type: none"> • Best for hollow parts with thin walls • Threads possible • Maintain generous radii • Pay attention to parting line • Draft angles not required • Min section ~ 0.25mm • Max section ~ 6mm

	and finish possible (higher pressure → better finish)	<ul style="list-style-type: none"> • Must consider creep and chemical stability of product 	
Roto-Molding (suitable for 100- 1000 units)	<ul style="list-style-type: none"> • Lead time typically several days • Little material wasted • Low tooling costs • Low equipment costs • Finishing costs low • Good surface detail 	<ul style="list-style-type: none"> • Low production rate (3-50 pieces/hr) • Moderate labor costs • Interior surface finish cannot be controlled 	<ul style="list-style-type: none"> • Best for large, hollow, uniform wall thickness parts • Long thin projectiles not possible • Maintain generous radii • Can mold in metal • Large threads possible • Pay attention to parting line • Avoid large flat surfaces—distort • Draft angles should be >1 degree • Min section ~ 0.5mm • Max section ~ 13mm
Continuous Extrusion (economical for 1000 kg of profile extrusion)	<ul style="list-style-type: none"> • High production rates (~60 m/min for tube sections) • Low labor • Little material wasted • Low finishing costs 	<ul style="list-style-type: none"> • High tooling costs • Moderate to high equipment costs • Toxic/volatile gases may be released during process • Lead time typically weeks • Moderate flexibility due to dedicated molds but short change-over and set-up times 	<ul style="list-style-type: none"> • Good for complex, thin-walled open or closed profiles • Requires uniform cross-section (post-op needed for additional features) • Draft angles not required • Min section ~ 0.4mm • Max section ~ 150 mm • 1-150 mm diameter tubes/rods • Can be sent in lengths to developing countries
Metals			
Sheet Metal Shearing and Forming (economical for >10,000 units if dedicated tooling is required)	<ul style="list-style-type: none"> • High production rates (~3000 pieces/hr for small components) • High degree of automation possible • Potentially little material wasted if planned well • Low to moderate labor depending on level of automation • Low finishing costs (only deburring, trimming and cleaning) • Good surface detail 	<ul style="list-style-type: none"> • Lead time typically weeks depending on level of automation (can be days for simple bending processes) • Moderate to high tooling costs • Variable equipment costs (low for simple bending machines) 	<ul style="list-style-type: none"> • Complex cut patterns possible in two dimensions and complex forms possible through progressive operations • Min sheet thickness ~ 0.1mm • Max sheet thickness ~ 13mm for shearing, 25mm for bending, 6mm for roll/stretch forming • 2-600mm diameter for deep drawing and

			10mm-1.5m width for roll forming • Must inspect and maintain against die wear and breakage
Continuous Extrusion (viable for both short and long production runs)	<ul style="list-style-type: none"> • High production rates but dependent on size and complexity (up to 12m/min) • Little material wasted • Low labor • Low finishing costs (only needs to be cut to length and deburred) • Good to excellent surface detail 	<ul style="list-style-type: none"> • Lead time typically weeks • Moderate flexibility due to dedicated tooling but short change-over and set-up times • Moderate tooling costs • High equipment costs 	<ul style="list-style-type: none"> • Good for long products with uniform cross-sections • Must pay attention to direction of extrusion—details perpendicular to direction require post-op machining • Requires generous radii • Min section ~ 1mm • Max section ~ 100mm • Warp and twist can occur • Can be sent in lengths to developing countries

Decision Analysis of Manufactured Components

Our quantities are projected to be over 50,000/yr (for each region specific design) after the one-year pilot program. These quantities drive our design decisions.

Lens - The only economical choice for lens material is clear plastic. Currently we favor acrylic, although other, less brittle options may be necessary if an acrylic lens fails to meet the requirements of the reliability testing. These will include drop tests and other usage simulations.

A convex lens shape (or a clear cover) is an appropriate candidate for injection molding. Tooling costs would be small, possibly less than \$20k. A multiple cavity mold would be possible for a small, simple geometry. Part prices may be slightly higher than similar sized opaque parts because of the additional quality and material issues relating to optically clear components. The manufacturing is also more challenging because of thick wall sections needed for a convex lens. However, these components are common in hand held lights, and outsourced manufacturing of molded lenses is very common.

Housing – A “clamshell” injected plastic housing (made with two halves mating together) is a good choice because it accommodates many different designs, and is easy to assemble and disassemble; for high-volume production, injection molding is quick and cost-effective. Metal housings are less suited for our lights, since these components are typically only cost effective for simple, rectilinear forms or where the durability of plastic is inadequate. We are continuing to consider specific choices for an injected molded housing. Surviving a drop test is a critical design constraint, however, we recognize that we may be using a relatively fragile PV panel (glass based single-crystal panels). These are bonded to plastic and resin coated; however, they may still break with a significant impact. Therefore, an indestructible housing is not a critical consideration if it does not prevent the panel from breaking.

Prototypes

Initial Field Prototypes

At the beginning of the quarter we sent a series of prototypes to the field, to test our basic assumptions about our target users. The modified flashlight, modified push light, and three-headed snake light are representative of the first batch of prototypes that we sent into the field. These are lights made with off-the-shelf parts, intended to illustrate different variables and elicit user reactions. Descriptions of these lights are followed by a summary of the feedback we received on them.

Modified Flashlight



Figure 9 - Modified flashlight

Point of View

The modified flashlight is a light for people who need a static indoor light source, but also need the ability to carry it with them. Our main modification was replacing the original incandescent bulb with a 1W LED.

User group

Families, night market vendors, cottage industry workers—portable task or ambient lighting.

Technical Specifications

- 2" diameter x 4", approx. 1lb
- Existing plastic housing
- Articulating arms allows light to be set up in any position, or recess to be carries.
- Dimmer switch allows variable brightness in the light
- Lens and reflector provide additional light optimization
- 4 AA batteries

Lessons learned

- Articulating arms will make an otherwise durable design vulnerable.
- Reflectors are not relevant to light optics for LEDs.
- Plastic lens covers reduce light output.
- There is more need for a static light than a portable one.

Modified Push Light



Figure 10 - Modified push light

Point of View

The modified push light is a light to hang on a wall or ceiling. Our main modification was replacing the original incandescent bulb with a 1W LED.

User group

Family, night market vendors, schools—ambient lighting where light doesn't need to be portable.

Technical Specifications

- 6" diameter x 1.5", approx. .5lb
- Existing plastic housing
- Light switches on and off when you press on the white diffuser part
- 4 AA batteries

Lessons learned

- This light does not survive the 6 ft. drop test.
- The diffuse white surface reduces light output by a fair amount.
- If mounted on wall, doesn't light room evenly. If mounted on ceiling, can be too high to light effectively, or too high to reach.

Three-headed Snake Light



Figure 11 - Three-headed snake light

Point of View

This light sits on a surface such as a table, bed, or floor, and you can aim it towards your work by bending the “snake” form. It is made from 3 separate .1W LED lights, taken from commercially available keychains; by turning on one LED at a time this light gives a good test of how much is the appropriate amount of light.

User group

Families, cottage industry workers—task lighting.

Technical Specifications

- Approx. 1” diameter, 16” length, .5 lb.
- Made from keychain flashlights and conformable tubing
- Separate switches for each LED
- Adjusting the tubing allows you to change the direction of the light

Lessons Learned

- To get a full range of light positions, the snake part has to be longer.
- Turning on one LED at a time gives good flexibility in the light output.
- Some cultures fear snakes, so the snake form might be unpleasant.

User Feedback on Initial Prototypes

Summary

The previous three prototypes are representative of many that we sent to the field at the beginning of the quarter. The prototypes were sent in different boxes—one box focusing on quality of light, another box focusing on form and usage, and so on. We sent the lights with disposable cameras and questionnaires to in-country contacts, who distributed them to representative target users.

User Feedback Surveys

The questionnaires sent with the prototypes included the following questions:

- What are the things that currently give you light (electric or non-electric)?
- Are there any other light sources you'd like to have? Do you think you will get these?
- How many hours a day do you use your current light source?
- Draw your ideal light.
- Tell us how you use each of the lights we gave you, and any problems you have had with it.
- Which of these three lights is most useful to you and why?
- If you could have one light, which one would it be?
- How much would you pay for each of these lights? (To get an idea of how much value this is, what else would you buy that costs this amount?)
- Which light is most similar to the one you currently use?
- Which light is the easiest to use?
- Which light is the best looking?
- Which light is the brightest?
- How many people could use each light at the same time?
- What time of day do you like to use each light?
- Which light would you use outside?
- Which tasks could you use each light for?

We received helpful feedback on these first shipments, at different times throughout the 10-week project. For the packages sent in week 3, Indian contacts replied to us by week 5, and we sent more packages to test more ideas. Chinese contacts replied by week 9, and Mexican contacts replied by week 10.

Photos From the Field

The following photos are a sampling from those we got in our initial user testing. Although the flash on the cameras blocks us from seeing how bright the conditions are, we can see what people use the light for, and how people interact around a small light. These are a sampling of photos taken in India.

The first two photos are of students at a boarding school in Barli, India, studying together in the hallways with a shared light.



Figure 12 - Students with ambient light from above



Figure 13 - Students below our modified push lamp

The next photos are of the family of Bharatsinh Patel in Ankali, India. This family has unreliable electricity—it works some hours each day, often not at night. The photos show them using the light for communicating and for working at night.



Figure 14 - Bharatsinh Patel, sewing below our three-headed snake light.



Figure 15 - Older girls reading with our modified flashlight, young boy with our three-headed snake light around his neck



Figure 16 - Men reading with our modified flashlight and three-headed snake light

The next group of photos, from rural Liangshan, China, show people using lights to illuminate their homes.



Figure 17 - Shelter for people and animal feed, visible through falling snow



Figure 18 - Livestock under a straw roof



**Figure 19 - Children with current lighting source—
kerosene in a can, mounted on house supports**



**Figure 20 - Our modified flashlight in the
home, hanging from house supports. The
light is in the same position in both
photos, but it is hardly visible in the
bottom photo.**



The next set of photos is from a more urban setting in China. They show lights being used in a small shop, and schoolwork by daylight.



Figure 21 - People in small shop, with lighting through the outside door



Figure 22 - Modified flashlight, used to illuminate part of the shop



Figure 23 - Students working by daylight

Component Prototypes

The PIC dimming circuit and hand-crank power generator were created to explore different components of the light system without attempting to integrate it all.

PIC Dimming Circuit

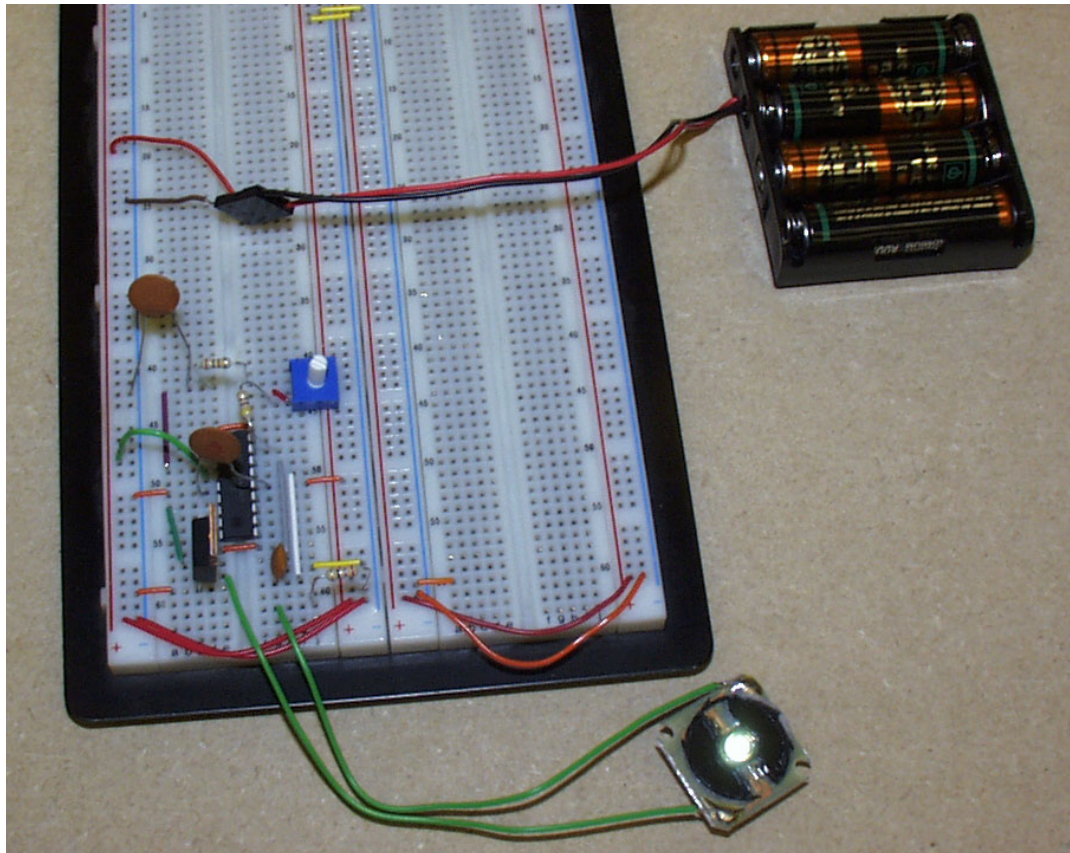


Figure 24 - PIC dimming circuit

Point of View

This circuit demonstrates dimming a white LED—a possible add-on for any of the prototypes.

Technical Specifications

- PIC-based circuit
- Breadboard prototype

Bill of Materials and Estimated Cost

Table 16 - PIC dimming circuit components and pricing

Component	Quantity	Cost (retail)	Total
Luxeon Star	1	\$2.78	\$2.78
PIC- 16F84A	1	\$3.70*	\$3.70
MOSFET- IRLZ34N	1	\$0.70	\$0.70
oscillator- 10 MHz	1	\$0.60	\$0.60
potentiometer- 20k	1	\$0.65	\$0.65
resistors- 5,100,470	3	\$0.01	\$0.03
capacitor- 100pF	1	\$0.10	\$0.10
switch- 2 position	1	\$0.10	\$0.10
batteries- AA	4	\$0.50	\$2.00
battery holder- 4 AAs	1	\$0.80	\$0.80
Total		\$11.46	

* This PIC is much more expensive than those we continued to develop with.

Usage Scenario

If the users want a less bright light or want to reduce battery use, they can turn a knob to dim the light.

PIC Functionality

In this circuit, the PIC measures an RC rise time and sets the duty cycle of the LED accordingly. The LED is being multiplexed—turned on and off at a frequency which is high enough that the eye can't detect flickering. Changing the duty cycle means changing the percentage of time that the LED is turned on, which affects the perceived brightness of the light. Below is a schematic for the PIC dimming circuit.

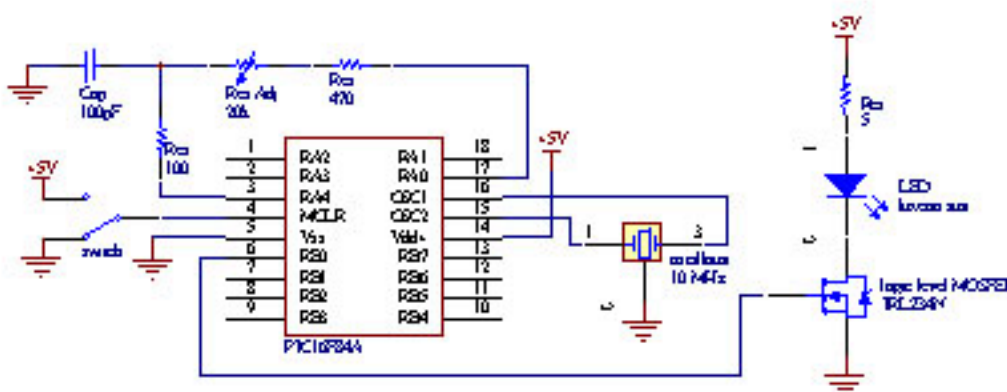


Figure 25 - PIC dimming circuit schematic

To detect rise time, the PIC sets two outputs high, RA0 and RA4. The first output is a standard I/O line, which goes high when you set it high. The second output is an open drain output, which goes high only if you set it high and it is connected to a +5V signal—otherwise it stays low. The first output is connected to the second output by an RC combination, so there is a delay corresponding to the RC rise time between when you set the outputs high and when the

second output actually goes high. The RC is made up of a capacitor and a resistor in series with a potentiometer, so the rise time changes as the potentiometer dial is turned.

The duty cycle control is simple—each time the PIC cycles through the program, it turns the LED on for the period corresponding to the rise time, then turns the LED off for a fixed delay time. The percentage of time that the LED is on depends on the ratio of the rise time to the total time:

$$\text{duty cycle} = (\text{rise time}) / (\text{rise time} + \text{delay time})$$

The frequency of the multiplexing depends on the fixed delay time and the rise time, so it is not constant:

$$\text{frequency} = 1 / (\text{rise time} + \text{delay time})$$

The result of all of this is a circuit where the LED is bright with a high duty cycle, and dim with a low duty cycle.

Lessons Learned

- Dimming is not a major design goal. The light output and battery usage are low already, so dimming is not necessary. It is only desirable as a no-cost item.
- Dimming with a PIC changing the duty cycle of the LED requires extra components (an RC configuration with a potentiometer.) If the circuit has a PIC controlling a switching circuit, you can accomplish dimming by changing the amount of current through the LED, and this requires no extra components—the user could just press and hold down on the power switch to dim instead of turning an actual knob.

Hand-crank Generator



Figure 26 - Hand-crank generator

Point of View

This prototype is an exploration into mechanical power generation and storage. When the switch is off and no power is going to the light, the crank is easy to turn. When the switch is on and the generator powers the light in real-time, the resistance is very high, and one tires after a minute or so of cranking.

Technical Specifications

- 12W Halogen lamp
- Geared up hand-crank power generator
- Light switch
- Pine wood base

Lessons Learned

- Mechanical power generation can be burdensome and tiring; there is a big difference of the feel of the crank for load and no load.

Midway Prototypes

The midway prototypes begin to integrate the light components, and to explore different ideas for form and usage.

Ambient Hanging Light



Figure 27 - Ambient hanging light

Point of View

This light is meant to be the basis of an incremental move towards inexpensive and sustainable LED lighting. It seeks to gain early acceptance by using a familiar flashlight configuration and by using commonly used and available batteries. As the technology gains acceptance and costs decline, the light could be used in conjunction with rechargeable batteries and a home PV recharging system at a later date. The light can be used as ambient light for multiple people at a table, or as a handheld light.

User group

Poor rural families, urban families connected to an unreliable grid.

Technical Specifications

- 4.25" diameter, 4.5" high
- Several injection molded or rotationally molded parts, possibly a sheet metal chassis.
- 2 1W Luxeon Stars (batwing pattern)
- 4 AA-size batteries, preferably alkaline

Bill of Materials and Estimated Cost

Table 17 - Ambient light components and pricing

Component	quantity	estimated unit cost	total
LED - Luxeon Star	2	2.78	5.56
batteries	(sold separately)	.60	0.00
housing	1	1.00	1.00
circuitry + internal wiring	1	1.00	1.00
battery holder	(molded in)	0.00	0.00
Total		\$7.56	

Usage Scenario

The light can be suspended from the ceiling, a rafter, or a side wall of a dwelling and used to light a large area, or it can be hung over a stand at a night market, using the handle as a hook for hanging. It can also be used as a handheld light or a portable light. The lights are intended to be inexpensive enough that people can save money to purchase more lights, eventually lighting an entire room. The light uses disposable batteries, purchased separately; when the batteries are drained, they are discarded and replaced.

Lessons Learned

- There is little visible difference between two LEDs and one.
- There should be a feature to prevent the light from rolling when placed on a flat surface.
- The switch should be large and easy to operate.
- A reflector is not useful.
- The LED should be recessed since looking directly at the emitter is unpleasant.
- Battery access is crucial.

Multitask Light



Figure 28 - Multitask light

Point of View

This light is designed for a user group that may not have any sources of light more powerful than a small flame. Therefore, our device may get used for a wide variety of activities including housework, craft work, night travel, displaying goods at markets, or ambient light for social activities.

The prototype explores methods to provide a versatile light for both task and ambient uses. The light uses two LEDs with the option to use one or both depending on need. An adjustable lens tests focusing optics, which have focused and non-focused light for task and ambient uses.

User Group

Night market vendors, cottage industry workers, rural families.

Technical Specifications

- 2 1W LEDs: one narrow beam (lambertian) and one wide beam (batwing)
- Multiposition focusing optic
- 4 AA batteries
- Three-position switch
- Faceted housing for multiple beam angles

Bill of Materials & Estimated Cost

Table 18 - Multitask light components and pricing

Component	quantity	estimated unit cost	total
Luxeon Star	2	\$2.87	\$5.74
Batteries	4	\$0.60	\$2.40
Housing	1	\$1.00	\$1.00
circuitry + internal wiring	1	\$1.00	\$1.00
Total		\$10.14	

Usage Scenario

The light can be hung from a ceiling, mounted to a wall, placed on a table, or held in the user's hand. The batteries could be charged by an integrated solar panel or removed and exchanged with charged batteries, charged independently or through a communal charging station.

Lessons Learned

- There is little visible difference between two LEDs and one, if they are very close together.
- Focusing the light is a much better method for bright task lighting than adding additional LEDs.
- The housing feels big for such a small light source.
- Holding the light using an "iron"-like handle drew criticism from some because it is perpendicular to the standard direction of a flashlight, but in use the "aiming" was comfortable.

Snake Light



Figure 29 - Snake light

Point of View

This design would allow the light to be used as:

- task lighting with little/no glare
- ambient lighting from a table, ceiling, or wall
- portable flashlight hung around neck, perched on head, wrapped onto bicycle, or held in hand

User Group

Cottage industry workers, families, night market vendors, people traveling on bicycle or animal, people walking outdoors at night.

Bill of Materials and Estimated Cost

Table 19 - Snake light components and pricing

Component	quantity	estimated cost	total
Luxeon Star	1	\$2.78	\$2.78
housing, wire, etc.	1	\$1.00	\$1.00
Circuitry	1	\$1.00	\$1.00
switch- 2 position	1	\$0.10	\$0.10
batteries- AA NiMH, 2Ahr	4	\$0.60	\$2.40
Total		\$7.28	

Usage Scenario

The light can sit on a table pointing downwards to illuminate a user's task without glare, possibly being shared by multiple people. For ambient light to talk or eat with people, the light can still be on a table, simply pointing upwards, or it can be hung from a hook in the wall/ceiling, or draped over a convenient object like a rafter. Several lights can be used together side-by-side

for more illumination; perhaps the battery-holding base parts could be built to snap together for designed-looking light clusters.

The light is supremely portable; it can be wrapped around the handlebars of a bicycle or the horns of a yak, draped around the neck or perched on the head, carried in the hand or wrapped around the arm, even attached to clothing. This makes it useful for nighttime travel, household chores in multiple locations, or trips to the outhouse. As before, more units can be combined for brighter light; if the user wants the lights to be all one unit, they can twine the snakes together.

Lessons Learned

- The versatility of this light is exciting to users.
- This version of the snake light is designed to have batteries in the base and wires through the copper tubing to the light. In order to eliminate the cost and potential unreliability of external batteries, we could consolidate the batteries and light package. In this case, the snake base could be an add-on to any self-contained light.

Mod 3



Figure 30 - Mod 3 light

Point of View

The Mod 3 appeals to both the poor and the economically better off by offering the light in individual modules that can be bought singly or as a set. With 1 Luxeon LED and 4 AA batteries, the Mod 3 offers a low entry point when bought as a single unit. The user then has the option to upgrade by buying additional modules that can be combined to create a set of two or three LED light units. Styling allows for versatile handheld, tabletop or ceiling mount use.

User Group

Very poor families buy 1 light, with the option to buy more later. Less poor families buy a set of 2 or 3 lights. Different types of light output satisfy the needs of home and night market users.

Technical Specifications

- Per module: 3" x 2" x 6", approx. 6.5 oz
- An assembled set of 3: 4" x 4.5" x 6", approx. 20 oz.
- Stamped Al sheet metal housing over a injection molded plastic core
- 1 1W Luxeon LED
- Requires 4 AA NiMH batteries at 1800 mAh per battery
- Optional holder/charging device for recharging batteries using a PV panel or an adapter that draws power from the grid

Bill of Materials and Estimated Cost

The prices listed below are for a single module.

Table 20 - Mod 3 components and pricing

Component	quantity	estimated unit cost	total
Luxeon Star	1	\$2.78	\$2.78
housing, wire, etc.	1	\$1.00	\$1.00
circuitry	1	\$1.00	\$1.00
switch- 2 position	1	\$0.10	\$0.10
batteries- AA NiMH, 1800mAh	4	\$0.60	\$2.40
battery holder- 4 AAs	1	\$0.10	\$0.10
lens	1	\$0.80	\$0.80
Total		\$8.18	

UsageS

A very poor family that is either not on the electrical grid, or has limited access to it, can buy a single module. A night market owner can buy a single module or a set of two or three. The multiple units can be combined to form a coherent set or can be strung separately to light the wares. Though the brightness of a single module is not nearly enough to compete against an incandescent bulb, the light is sufficient to accomplish tasks, enable short-term reading and light a full table of wares for sale. The light can be used as a hanging light as well as a tabletop light or flashlight. It will provide a safer—less fire prone and elimination of noxious fumes—alternative to fuel-based lighting. This light will potentially increase the user's income by assisting with the home cottage industry or with sales at the night market. With the complete system, the user can either recharge the batteries through solar power or through the grid and doesn't have to depend on reliable electricity to power the light. Once the user generates income with the light, he or she can increase the light intensity by purchasing additional modules. With 3 units, there is adequate lighting for most household or market tasks.

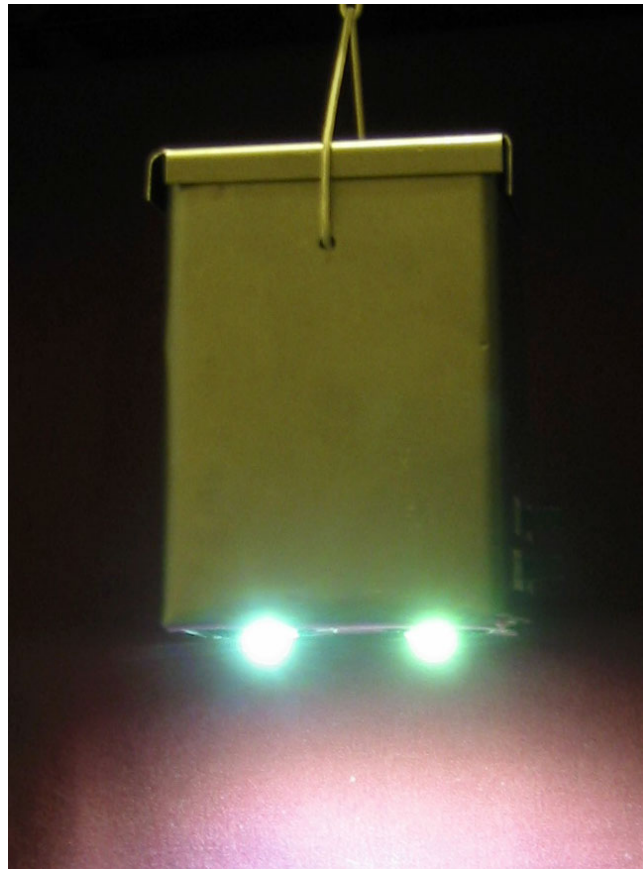
Lessons Learned

- The direction of light is not currently ideal: in certain positions, the light shines at the users' faces instead of the workspace. Lenses and the angle of the light need to be explored, especially when multiple lights are combined to form a set.
- Appearance counts. The sleek silver metal and black trim look attracted much attention and gave the set a higher perceived value, according to our observers.
- Ergonomics of a handheld light are important.
- Extrusion is highly economical and extruded tubes can be sent to the developing country to be cut to size and finished.
- If a family were to buy 3 separate lights, it's likely that they would often want to spread them out instead of docking them together.

Upgradeable Hanging Light



Figure 31 - Upgradeable hanging light



Point of View

This light allows very poor people and less poor people to buy the same light package; those who buy it with 1 LED can upgrade later to 2. This gives people the chance to invest in stages, and it allows LUTW to produce one light in high volumes.

User Group

Very poor families buy with the light with 1 LED, with the option to upgrade later. Less poor families buy it with 2 LEDs.

Technical Specifications

- 1.5" x 2.5" x 3.5", approx. 1lb
- Sheet metal housing, for manufacturability and ability to act as heat sink
- 1-LED model comes with all components except second LED and set of 4 batteries.
- second LED is soldered to existing wires on light.

Bill of Materials and Estimated Cost

The price of this light is optimized for a low-cost 2 LED/8 battery light. The family that will never upgrade to 2 LEDs is paying for about \$.30 of extra components—a second switch (included in circuit cost) and a second battery holder. However, by producing one light in high volumes instead of different models for different user groups, there could be economy of scale savings in the manufacturing. The costs for the light components are shown below.

Table 21 - Upgradeable hanging light components and pricing

Component	one LED			two LEDs		
	quantity	estimated unit cost	total	quantity	estimated unit cost	total
LED - Luxeon Star	1	\$2.78	\$2.78	2	\$2.78	\$5.56
batteries - 2Ah NiMH AA	4	\$0.60	\$2.40	8	\$0.60	\$4.80
housing - sheet metal	1	\$1.00	\$1.00	1	\$1.00	\$1.00
circuitry + internal wiring	1	\$1.00	\$1.00	1	\$1.00	\$1.00
battery holder - 4 AAs	2	\$0.10	\$0.20	2	\$0.10	\$0.20
Total		\$7.38			\$12.56	

Usage Scenario

A very poor family buys the light with 1 LED. To use the light, family members insert 4 batteries. They put the switch for number of LEDs to the 1 LED position, and they use the on-off switch to control the light.

If the family wishes to upgrade from 1 LED to 2 LEDs, they take their light to the local LUTW dealer. The light already includes 2 switches, 2 battery holders, and wire leads for the second LED, so all the dealer needs to do is solder on the new LED. The family inserts 4 more batteries, turns the switch to the 2 LED position, and uses the on-off switch to control the light. They now have the flexibility of using either light setting (1 or 2 LEDs), and either battery setting (4 or 8 batteries). A less poor family buys the light with 2 LEDs to begin with.

Lessons Learned

- There is little visible difference between two LEDs and one.
- For the 2-LED configuration, it is convenient to be able to turn off half of the light to save batteries when they are running low.
- A hanging light provides a nice, even light to the surface below. Looking straight into the LEDs burns your eyes.

Flexi-light



Figure 32 - Flexi-light

Point of View

This light offers the user a variable lighting solution:

- Flexible task lighting from a desktop, or ceiling or wall. Attempts to get light source as close to the task as possible, without glare.
- Ambient lighting from a table, ceiling, or wall
- Portable as a flashlight

User Group

Rural families, night market users, students, industry workers.

Bill of Materials and Estimated Cost

Table 22 - Flexi-light components and pricing

Component	Quantity	estimated unit cost	total
Luxeon Star	1	\$2.78	\$2.78
housing, wiring, etc.	1	\$1.00	\$1.00
circuitry	1	\$1.00	\$1.00
switch- 2 position	1	\$0.10	\$0.10
batteries- AA NiMH, 2Ahr	2	\$0.60	\$1.20
battery holder- 2 AAs	1	\$0.10	\$0.10
Flexible wire	1	\$0.50	\$0.50
Total		\$6.68	

Usage Scenario

This light is intended for users who want a lighting solution that can quickly adapt to many tasks. The light excels at specific task lighting. Given the limited light output of LEDs, even at the 1W Luxeon level, it is important to place the light source close to the task. For dish washing, book

reading, sewing, or any of a wide variety of tasks, the light is made to sit near the task and shine down on the work area, minimizing glare while also getting the light source as close to the task as possible. The light can also serve as a flashlight, as the user would grip the round base while carrying the light outside the home, and it can be hung from the ceiling, providing general room illumination.

Lessons Learned

- Flexible unit needs to be quite rugged and could quickly raise the system cost.
- The small size of LEDs allows for innovative positioning, beyond typical lighting designs.

Comparison Matrix for Midway Prototypes

Prototype	Pro	Con	Suggestions
Ambient Hanging Light	<ul style="list-style-type: none"> • Can Hang/Hook on • Portable • Aesthetic – roundness • Durability • Size 	<ul style="list-style-type: none"> • Roundness - not really table-settable • Can scuff face/optics • Difficult to hang close to table • A bit difficult on bike 	<ul style="list-style-type: none"> • Single LED • Hexagonal - honeycomb - can put together a la Mod 3; think about this when determining radius • Taper handle to spread out at end • Incorporate curvature for bike • Spring-loaded clamp handle
Multitask Light (“Iron light”)	<ul style="list-style-type: none"> • LED level above table • Toggle b/w 1 and 2 LEDs • Sliding optics • Can assemble 2 together 	<ul style="list-style-type: none"> • Too big • Sliding optics – durability • Aesthetics 	<ul style="list-style-type: none"> • Single LED • Round edges • Tad smaller • Combine with Hanging Ambient • Rotate disc (pie shape with different pie slices as different lenses) to achieve sliding optics • Diffusers
Snake Light	<ul style="list-style-type: none"> • Flexibility • Aesthetic appeal • Novelty (Indians liked) • Popular 	<ul style="list-style-type: none"> • Cu right material - work hardening? • Wired embedded in tubing complex – voltage drop across length? 	<ul style="list-style-type: none"> • Incorporate loops • Cu can be possibly replaced by existing materials in countries • Linkages instead (lots of parts, but each the same) • Encapsulate batteries with light - store extra batteries as the counterweight, or as the neck • Maybe accessorize the concept, but develop one of the other lights as the head • Gooseneck tried earlier but too \$\$\$

Mod 3	<ul style="list-style-type: none"> • SEXY • Extrudable --> cheap • Can assemble locally • Greater cone angle with all three 	<ul style="list-style-type: none"> • Usefulness of angle? - light shining up • Too heavy to hang together • No functionality to facilitate hanging • What does 3 together do for you? • A little too low on the table • Psychological issues if can only ever afford incomplete set 	<ul style="list-style-type: none"> • Incorporate flip-able optics • Incorporate legs (a la standing flashlight) or hooks • Have a bunch of holes on side for choice of hanging • Market separately instead of as set of 3 • Chandelier configuration
Upgradeable Hanging light	<ul style="list-style-type: none"> • Form – simple • Toggle b/w 1 and 2 LEDs • Easy to manufacture • Can hang well - symmetry 	<ul style="list-style-type: none"> • Form - reaction of light in a box? Familiar? • Need 2 LEDs? • Ergonomics • Ability to set down 	<ul style="list-style-type: none"> • Can do fewer batteries • Band-Aid boxes • Cigarette box form- with flap/hood as a reflector/stand

Lessons Learned from Midway Prototypes

- The light of an LED is most pleasant when it shined on the workspace from above—this gives a bright, even light without forcing people to look straight at the point source.
- If you move an ambient light close to a workspace, it becomes a task light.
- If you focus a beam with optics, you minimize the light wasted on the sides. Diffusers tend to reduce total light output with low transmission efficiency, while lenses redirect light with high transmission efficiency.
- With a power boost circuit, a Luxeon LED can be powered with 2 AA batteries.
- We believe that lights should have 1 Luxeon Star instead of 2 or 3 for several reasons:
 - Two LEDs are more effective when spread across some distance than when grouped together
 - The power generation requirements and their physical forms are quite different for 1-LED and 2-LED lights
 - Light Up The World will drive down their manufacturing costs if they produce only one light in high volumes
- Feedback from the field indicates that users like lights with substantial size and weight—it should feel strong, robust, and reliable if they are going to invest in it.

Final Prototypes

The designs that follow represent a culmination of 70 days' worth of research, testing, interviewing, prototyping, and brainstorming. Based on information that came back from our users in China, India, and Mexico, we iterated on our first prototypes to create three new light designs.

The first design is meant to be the lowest cost solution that includes a source for power generation (a solar panel) and a battery for power storage (1 NiMH battery). The second design is a hanging light with no power generation for users in Mexico and instead uses 2 D-cell alkaline batteries for power. The third is a hanging light that includes a source for power generation (a solar panel) and batteries for power storage (2 NiMH batteries) for users in China and India.

Our decisions about each light were made based on user research for each country – we spoke with anthropologists, business experts, and people who have lived in each country to understand what the culture and life are like for our users. The information we received back is still not complete, and so the designs may not be perfectly suited for our users. Our next steps are to take these prototypes into the field and observe how our users interact with and experience them.

“El Cheapo” Solar Flashlight



Figure 33 - El Cheapo solar flashlight

Point of View

This light is called “El Cheapo” because it gives users access to a complete light system at a low cost. It charges, powers, and lights, all in one rugged housing. Using .1W LEDs, we reduce the power generation requirements and take advantage of proven solid-state lighting that is long lasting, robust, and reliable.

User group

Poor, off-grid families can use this complete system, needing to buy more batteries very rarely. With the rugged housing, the solar panel is protected. And with solid-state lighting, there is no need for bulb replacement.

Technical Specifications

- 3” dia, x 7” long, approx. 1-lb.
- Injection-molded plastic for the outer housing (protects inner housing)
- Injection-molded plastic for the inner housing (holds batteries, reflector, and bulbs)
- 3 .1W Nichia white LEDs comprise the “bulb”
- Driver circuit programmed for constant light output with a low battery flash warning
- Solar panel output approx. 1.2V
- 1 NiMH battery @ 1800 mAh per battery

Development of Prototype

The El Cheapo Light prototype was created by retro-fitting an existing all-in-one flashlight with white LEDs instead of its incandescent bulb. By utilizing existing technology, we can extend the battery life of the rechargeable batteries by replacing the wasteful incandescent bulb with three highly efficient 0.1W white LEDs. In this way, we can piggyback on the tooling that already exists for this product.

Manufacturing

This solar-based light consists of a photovoltaic (PV) panel, an LED and driver circuit, 1 AA battery and wiring, and a housing (including optics). The PV panel, batteries, LED(s), and driver circuit will be purchased complete. The housing will be injection molded. This housing is a basic “clamshell” design where two mirror image halves are fastened together. Fasteners will be small screws and will allow the housing to be opened for changing worn out rechargeable batteries.

Bill of Materials and Estimated Cost

The price of this light is optimized for a low-cost 3 LED / 1 battery light. By producing the light in high volumes, there could be economy of scale savings in the manufacturing. The costs for the light components are shown below.

Table 23 - El cheapo flashlight components and pricing

Component	quantity	estimated unit cost	total
Nichia 0.1W LED	3	\$0.16	\$0.48
batteries: 1.8Ah NiMH AA	1	\$0.60	\$0.60
outer housing	1	\$1.00	\$1.00
inner housing	1	\$1.00	\$1.00
circuitry + internal wiring	1	\$1.00	\$1.00
solar panel	1	\$1.50	\$1.50
Total		\$5.58	

Usage Scenario

A very poor family that is either not on the electrical grid, or has limited access to it, buys a complete system. The light is sufficient to accomplish tasks and enable short-term reading. We envision the light to help light the way when any members of the family need to go outside at night. As well, it will help in reducing the noxious fumes produced by fuel-based lighting. We also envision the light to help this family accomplish tasks that could potentially increase income. For instance, after a day in the fields, a mother might want to supplement the family's income by making stools from bamboo. If she doesn't have sufficient lighting, she's likely to hurt her hands, as well as her eyes. With our complete system solution, she doesn't have to worry about electricity powering her light. It has been powered by the sun and would have a life of up to 6 hours. In the morning, as soon as the sun is up, the mother will place the light outside with the solar panel facing as directly at the sun as possible.

Lessons Learned

- 3 .1W Nichia LEDs give approximately 1/6 of the light of a single 1W Luxeon Star, but the light is sufficient for working, reading, and conversing.
- It is possible to make a light that has a complete power and charge system for well less than \$30.

Hanging Ambient Light - Mexico



Figure 34 - Hanging ambient light



Point of View

Intended for use in rural Mexico, the hanging ambient light provides enough light to illuminate a room. It gives users the option of hanging the light over an area or a task, or hand-holding it while moving around.; it has small flats on its edges so that it can be set down on its side. Its form factor is reminiscent of present technologies, so that users will recognize its function through its form. The light operates on two D cell alkaline batteries—the most abundant and available batteries in Mexico. The Luxeon Star extends the battery life over incandescent lights, allowing the users to buy new batteries less often.

User Group

Meant primarily for home use, the light can be hung from the ceiling. It is meant for ambient lighting to help illuminate light tasks around the house. It would be used briefly in the morning, and for approximately 3-4 hours in the evening. It could potentially lead to extra income for users if they can use the light to create and ultimately sell hand-made products. The lamp can also be used for short trips outside in the evening or early morning. Because the batteries are alkaline, opening and closing the lantern will occur often. The rotate and lock mechanism provides a simple robust solution to long-term wear.

Technical Specifications

- 4" dia. x 5.5" height, approx. 16 oz (with batteries installed)
- Injection molded plastic housing made in two parts that screw together
- 1 1W Luxeon LED
- Requires 2 D cell alkaline batteries at 2000mAh
- Step-down driver circuit, for 2 D cells and 1 Luxeon Star LED

Development of Prototype

The Hanging Ambient Light prototype was made from Renshape, a hybrid material that lies somewhere in between wood and plastic with respect to its machining properties—it machines like wood but has no grain. The screw mechanism was added after the two forms of the handle and housing were developed by gluing in two strips of styrene plastic. The housing was made just large enough for 2 D cell alkaline batteries to fit.

Manufacturing and Housing

The housing is a clamshell shape with a threaded cap and base designed to make batteries easily accessible. Nested in the clamshell are the optics, electronics, and batteries, as shown in the exploded-view sketch to the right. The geometry is relatively simple. It is the form that primarily dictates the need for a molded component.

Injection molding is the most economical option for the targeted production quantities with a relatively simple form. We have chosen to design very simple molded forms (with the possible exception of the mating threads where necessary). This means there are no undercuts or any need for cams or cores or anything beyond a standard two-part mold. We have not yet quoted tooling costs. This will be partially determined by the number of cavities made. It is likely these tools will initially be single cavity, with a layout designed to accommodate additional cavities in the future.

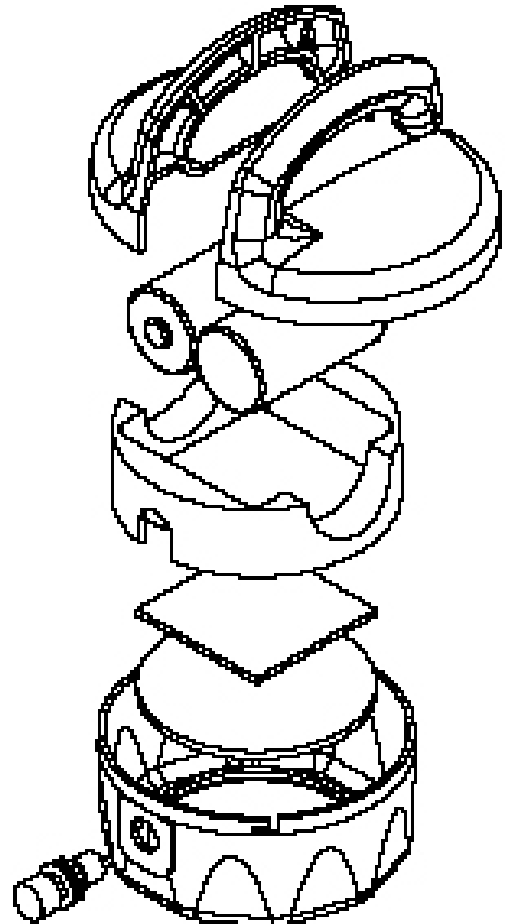


Figure 35 - Exploded-view sketch of hanging ambient light

Optics

This prototype uses clear acrylic sheet to seal the light package and to protect the LED. This acrylic sheet does not provide any optics and has high transmission efficiency, so the beam from the LED should not change.

Circuit

The circuit is in a step-down configuration, for 2 D cells and 1 Luxeon Star LED.

The three sets of red and white wires lead to the LED, the switch, and the battery pack. The board and PIC were provided by Kurt Kuhlmann. See Appendix 0 for circuit schematic.

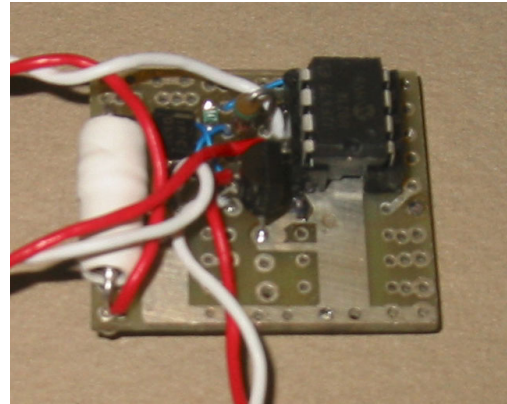


Figure 36 - Step-down circuit

Bill of Materials and Estimated Cost

Table 24 - Hanging ambient light components and pricing

Component	Quantity	estimated unit cost	total
Luxeon Star LED	1	\$2.78	\$2.78
housing, wire, etc.	1	\$1.00	\$1.00
circuitry	1	\$1.00	\$1.00
push button switch- 2 position	1	\$0.10	\$0.10
batteries- D alkaline, 2000mAh	2	\$0.60	\$1.20
battery holder- 2 Ds	1	\$0.10	\$0.10
Total		\$6.18	

Usage Scenario

Household use - The family awakens before dawn and hangs the light from a string on the ceiling above the stove to provide light while preparing breakfast. Once everyone has eaten and the sun has risen, the family switches off the light and leaves it where it hangs.

Cooking dinner is facilitated by the presence of the light. When dinner has been cooked, the food and the light are moved to the center of the room. The family eats around the light and then gathers around to sew garments for a couple of hours before bed. The garments will be sold at the market and will raise extra income for the family. When they tire, they switch off the light and go to bed.

When the batteries run out, the handle and endcap unscrew from each other and the batteries can easily be replaced. Since D cell batteries are the most common and abundant in Mexico, it is a quick run to the local market to pick up more batteries for the light.

Lessons Learned

- Battery usage and removal was a concern for us, so a simple robust design was required to prevent wear and tear over time. The quarter-turn screw-and-lock mechanism was a simple yet strong answer to this concern.
- The hook handle makes it easy to hang and grip the light.
- When set down on a surface, the light is most stable when it is set down on its acrylic face. In order to minimize the possibility of scratching, we recessed the face; it could still be scratched, however, if placed down on a rough and uneven surface.

Solar Light - India and China



Figure 37 - CAD drawings for the solar light

Point of View

The Solar Light provides a complete integrated system of a light, energy storage system and energy generator. It includes one Luxeon LED, 2 AA NiMH batteries and a 1.2W single crystal solar panel in a robust steady state, injection molded plastic housing. In addition to providing a diffuse ambient light, the light can also deliver a more focused task light beam through the use of a lens that can be rotated into place.

User Group

Meant primarily for home and night market use, the light can be hung from the ceiling or from a nail against a wall, or placed on a table top. Ideal battery charging occurs in the wall hanging and tabletop positions in which the solar panel sits at a 45-degree angle to the sun. The form incorporates a handle that can be gripped for handheld use or used to facilitate hanging or security against theft.

Technical Specifications

- 6" x 4.25" x 4.5", approx. 5 oz
- Injection molded plastic housing made in two parts and screwed together with standard Philips screws
- 1 1W Luxeon LED
- Requires 2 AA NiMH batteries at 1800 mAh per battery
- 1.2 W single crystal solar panel yields 3V at 0.4 A
- Charging for 7.2 hours provides 4.2 hours of light
- 1 rotating lens accommodating both diffuse and focused light
- Step-up driver circuit, for 2 AA NiMH batteries and 1 Luxeon Star LED

Development of Prototype

The Solar Light prototype (pictured above and below) was made from ABS plastic by means of Fused Deposition Modeling (FDM). Conceived using Computer-Aided 3D modeling, the prototype was designed and then programmed into FDM software, where it was literally printed

in plastic, layer by layer. The 3D-printed ABS prototype was then sanded and painted. Then the circuitry was added to the innards, as well as the light and the lens.

Manufacturing

This solar-based light consists of a photovoltaic (PV) panel, an LED and driver circuit, 2 AA batteries and wiring, and a housing (including optics). The PV panel, batteries, LED(s), and driver circuit will be purchased complete. The housing will be injection molded. This housing is a basic “clamshell” design where two mirror image halves are fastened together. Fasteners will be small screws that allow the housing to be opened to change worn out rechargeable batteries.

Housing

The housing will be a clamshell that contains a small solar panel, moveable lens, and other electronics to make batteries easily accessible. The geometry is relatively complex, and the form primarily dictates the need for a molded component.

Injection molding is the most economical option for the targeted production quantities with a complex form. We have chosen to design very simple molded forms. This means there are no undercuts or any need for cams or cores or anything beyond a standard two-part mold. We have not yet quoted tooling costs. This will be partially determined by the number of cavities made. It is likely these tools will initially be single cavity, with a layout designed to accommodate additional cavities in the future.

Solar Panel

Power for recharging the batteries will be generated using an 8 cm x 11.5 cm, single-crystalline solar panel. The panel is rated to 3 volts at 0.4 amperes and after 4.2 hours of using the LED light, it will take 7.2 hours for a full battery recharge. The 1.2 Watt panel will cost \$2.50/Watt for a total of \$3.00, epoxy resin mounting included.



Figure 38 - Solar light optics

Optics

The optics are mounted on a rotating disc, shown below. Because of its low cost and ease of manufacturing, acrylic was chosen for the disc. By spinning the disc, the user can choose which optics to use—no optics, or a focusing lens. The lens is a standard injection molded lens, chosen for cost, ease of manufacturing and efficiency of light transmission. In this prototype the lens is the collimator available with Lumileds batwing LEDs; in other iterations we could explore molding our own lens.

Circuit

The circuit is in a step-up driver configuration, for 2 AA NiMH batteries (max voltage 2.4V) and 1 Luxeon Star LED (forward voltage 3.7V).

The switch, pictured with the circuit to the right, is a contact switch with a carbon-impregnated rubber pushbutton making the contact. The PCB and PIC were provided by Kurt Kuhlmann. See Appendix 0 for circuit schematic.

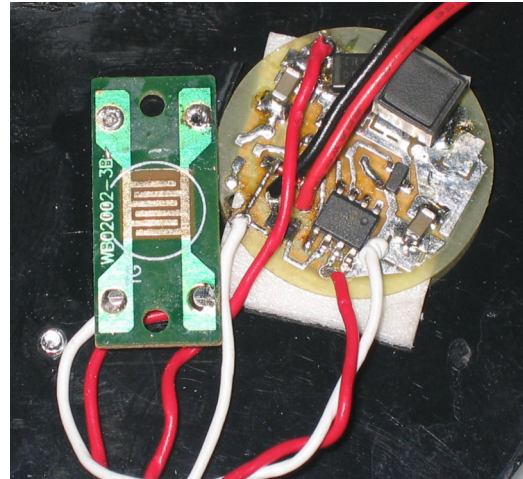


Figure 39 - Step-up circuit

Bill of Materials and Estimated Cost

Table 25 - Solar light components and pricing

Component	quantity	estimated unit cost	total
Luxeon Star LED	1	\$2.78	\$2.78
housing, wire, etc.	1	\$1.00	\$1.00
circuitry	1	\$1.00	\$1.00
push button switch- 2 position	1	\$0.10	\$0.10
batteries- AA NiMH, 1800mAh	2	\$0.60	\$1.20
battery holder- 2 AAs	1	\$0.10	\$0.10
lens	1	\$0.80	\$0.80
solar panel – 1.2W	1	\$3.00	\$3.00
Total		\$9.98	

Usage Scenario

Two user scenarios are presented—the experience of a household and that of a night market vendor.

Household use - The family awakens before dawn and hangs the light from a nail on the wall above the stove to provide light while preparing breakfast. Once everyone has eaten and the sun has risen, the family switches off the light and hangs it outside on a nail that has been driven into a post. A lock is threaded through the light's handle to protect it from theft. The family then heads out to the fields to work as the sun recharges the light's batteries through the attached solar panel, either hanging on a wall or sitting on the ground.



Figure 40 - Charging configurations for the solar light

The family returns after a full day in the field, without having to rush home to prepare dinner before dark. The freshly charged light is taken down from its nail outside and is brought into the house where it is again hung above the stove. Cooking dinner is facilitated by the presence of the light. When dinner has been cooked, the food and the light are moved to the center of the room. The light is hung on a nail on the wall, or by a string that falls from the ceiling.



Figure 41 - Home use of solar light

The family eats around the light and then gathers around to sew garments for a couple of hours before bed. The garments will be sold at the market and will raise extra income for the family. When they tire, they switch off the light and go to bed.

Night Market Vendor use - The night market vendor awakens early. His wife is preparing breakfast by the light. He joins her and they eat together as the sun rises. Afterwards, he bikes to the market with his goods and the light tucked into a trailer that he drags behind him. He sets up his wares and hangs the light by a string that is suspended between his and a neighbor's booth. The light will charge during the day to be ready when darkness falls on the market. After dark, the light illuminates the full table of wares, and as a result sales have tripled in the last month that the vendor has owned the light. As the market closes, the vendor packs up his goods under the glow of the light and then heads home, using the light to illuminate his path home.



Figure 42 - Night market use of solar light

Lessons Learned

- Because the solar panel is now attached to the light unit, the entire unit must be placed outside for charging. Therefore, weatherproofing will be an important issue that must be dealt with. Weatherproofing can range from including rubber O-rings in the assembly to including a plastic bag that will envelop the entire light when it is placed outside. This is an area that will require additional research to find the easiest and cheapest means.
- Because this light has been designed for multiple tasks (can hang by a string, hang on a nail embedded in a wall or beam, sit on a table or be held) and must be moved daily between the interior and exterior of the house, it must be easily engaged and disengaged from any mounting device (nail or string). We believe that the current design allows for this, but improvements could possibly be made and greater attention is paid to the interface of the light with the various mediums to which it can mount.
- The light must also be robust to accommodate the constant change in locations.
- Geometry is dictated by the size of the solar panel, the 45-degree optimal angle for recharging, and the gripability of the light.
- While the solar panel is much more robust than originally anticipated, care must still be taken to avoid scratching and scuffing of the surface. We have included short legs on the surface with the solar panel to elevate it above the surface upon which it sits. Other solutions are possible.
- We have been told that exposing the lens to sunlight could lead to opacity over time that would decrease the amount of light that can escape from the LED to the environment. Care must be taken in positioning the lens so that it receives minimal sunlight when the light is charging outdoors. In the hanging mode, the light is positioned downward to both protect the lens and direct the light to a usable location.

Conclusion & Next Steps

The SES team delivered three prototypes based on this research to Light up the World in a final presentation on June 6, 2003. The prototypes reflect two months of technical research, numerous design iterations, and a wealth of interactive feedback from a network of over 40 advisors and coaches from top companies and organizations. Between June and August 2003, a continuation team will continue the development process with a user testing/ pilot phase of 25 lights in target markets and a manufacturing feasibility study with contract manufacturers. Final iterations will commence from these processes.

Thanks

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- Chris Flink
- Joe Hei
- Jonah Houston
- Adrian James
- Rob Lister
- David Mallard
- Pascal Soboll
- Ben Tarbell
- Bryan White

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- Charlie Gay, Greenstar Corporation
- Kevin Guana, Lawrence Berkeley National Laboratory
- Mark Hodapp, Lumileds Lighting
- Steve Johnson, Lawrence Berkeley National Laboratory
- Evan Mills, Lawrence Berkeley National Laboratory
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- Ginger Turner

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- Scott "Sparky" Sullivan

Appendices

A. PIC dimming circuit assembly code

```
; dimming.asm
; use a potentiometer input to set PWM output for LED delay loop
; sally madsen

list p=16F84A
#include <p16F84A.inc>

__CONFIG    _CP_OFF & _WDT_OFF & _PWRTE_ON & _HS_OSC

; variable definitions
TimeCounter    EQU    0x0C
DelayCounter    EQU    0x0D

; bit definitions
; port A
rc_out          EQU    0
rc_in           EQU    4

; port B
pwm             EQU    0

; constant definitions
portAinsouts    EQU    0x0E    ; rc_out, rc_in outputs
portBinsouts    EQU    0xFE    ; pwm output
RCbitshigh      EQU    0x11    ; rc_out and rc_in high
RCbitslow       EQU    0x00    ; all bits low
DelayCount      EQU    0xFF

                ORG    0x000
                goto   Main
                ORG                0x005

Main:
; initialize PIC
    bsf    STATUS, RP0    ; set to bank 1
    movlw  portAinsouts    ; add portA settings to W
    movwf  TRISA           ; then move to portA register
    movlw  portBinsouts    ; add portB settings to W
    movwf  TRISB           ; then move to portB register
    bcf    STATUS, RP0    ; set to bank 0

    clrf   PORTA           ; set outputs to 0
    clrf   PORTB           ; set outputs to 0
    clrf   TimeCounter     ; clear time counter
```

Timerloop

```
; led on
    bsf    PORTB, pwm    ; led on

; set rc bits
    movlw  RCbitshigh    ; move RCbitshigh to W
    movwf  PORTA         ; then move to port A

Timer:
    incf   TimeCounter    ; increment time counter
    btfss  PORTA, rc_in   ; skip next instruction if rc in is high
    goto   Timer

; clear rc bits
    movlw  RCbitslow     ; move RCbitslow to W
    movwf  PORTA         ; then move to port A

; led off
    bcf    PORTB, pwm    ; led off

DelayLoop:
    addlw  DelayCount     ; add delay count to W
    movfw  DelayCounter   ; then move it to DelayCounter
    decfsz DelayCounter, f ; decrement DelayCounter
    goto   DelayLoop

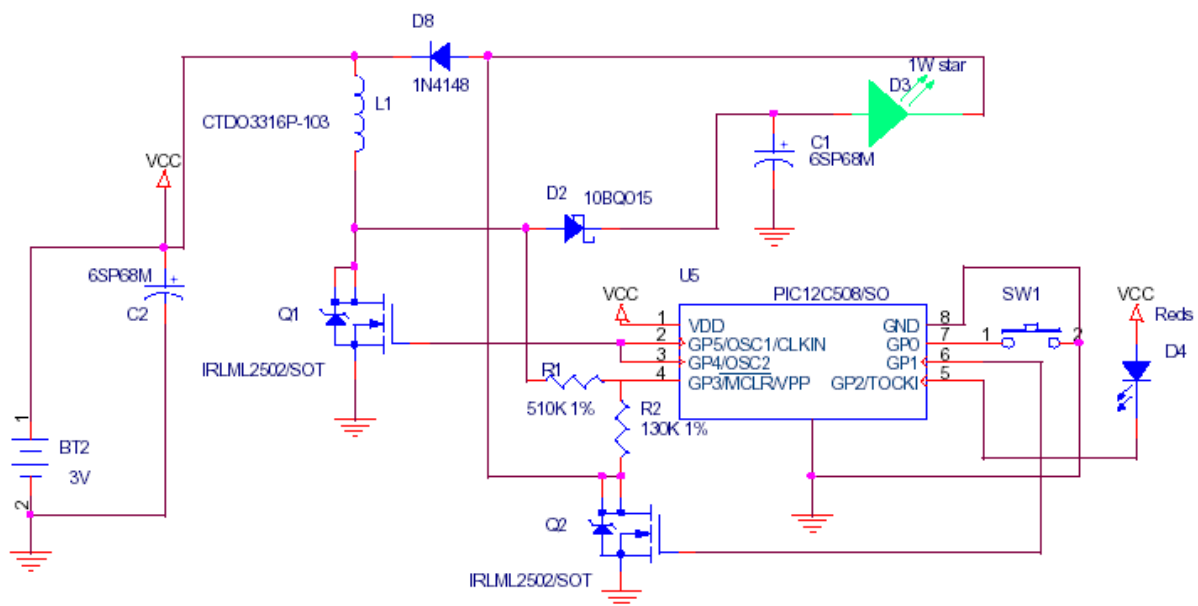
    goto   Timerloop      ; return to beginning

    nop
    end
```

[illegible]

- The switch marked SW1 is the power switch/dimming switch.
- VCC for this circuit is regulated to 5V. The label at pin 1 of the PIC should be 5V.
- The diode marked D1 could be replaced by a mechanical method of preventing reverse polarity of the battery.

C. Step-up circuit schematic courtesy of Kurt Kuhlmann



Notes about schematic

- The switch marked SW1 is the power switch/dimming switch.
- VCC for this circuit changes as the batteries drain. For 2 AA batteries, the max VCC would be 2.4V.
- The LED marked D4 is for debugging purposes only, and is not necessary for the final light design.