Solid State Lighting for the Developing World - The Only Solution

Rodolfo Peon, Ganesh Doluweera, Inna Platonova, Dave Irvine-Halliday, Gregor Irvine-Halliday

Light Up The World Foundation
Dept. of Electrical & Computer Engineering,
Schulich School of Engineering
University of Calgary
2500 University Drive N.W., Calgary, AB, Canada T2N 1N4

www.lutw.org

Peon, R., Doluweera, G., Platonova, I., Irvine-Halliday, D., Irvine-Halliday, G., Solid State Lighting for the Developing World - The Only Solution*, Optics & Photonics 2005, Proceedings of SPIE*, San Diego, 2005

Solid State Lighting for the Developing World - The Only Solution

Rodolfo Peon, Ganesh Doluweera, Inna Platonova,
Dave Irvine-Halliday*, Gregor Irvine-Halliday
Light Up The World Foundation
Dept. of Elec. & Comp. Engg., Schulich School of Engineering
University of Calgary
2500 University Drive N.W., Calgary, AB, Canada T2N 1N4

ABSTRACT

Approximately two billion people, one third of humanity still has no access to electricity, and thus relies on fuel-based lighting, a dangerous alternative of last resort that is unhealthy, expensive, and offers very poor levels of illumination. This lack of light makes it difficult to perform most evening activities including studies by children and adults alike and therefore represents a significant barrier to human development.
Over the past five years The Light Up The World Foundation (LUTW) has pioneered the use of the white light emitting diode (WLED) as an alternative home lighting solution, bringing clean, affordable light to thousands of non-electrified homes around the world.

The information presented herein is intended to increase awareness of the enormous potential possessed by this emergent technology, "Solid State Lighting" (SSL), to improve the quality of life of millions of people around the world. The feasibility of its implementation is demonstrated with results from comprehensive field experience and laboratory research work. The mutual economic, social and environmental benefits for both stakeholders and SSL suppliers are discussed. Strategies conducive to the dissemination of this technology throughout the developing world are also presented.

Keywords: Solid state lighting, sustainable development, alternative energy, social entrepreneurship

1. INTRODUCTION

Lighting is a basic human need like clean water, food, sanitation and shelter. In this new era of information and market globalization, appropriate lighting should be considered a human right, directly linked as it is to literacy and therefore education, a key component in human development: a well-educated population desires and tends to create healthier, safer, more democratic and peaceful communities.

It is estimated that two billion people have no access to electricity and thus live virtually in darkness after sunset. It is clear that the provision of light - a very precious commodity that many in the industrialized world take for granted - is only the beginning of a larger development process whereby lives and standards of living are improved in many tangible ways. LUTW's processes reorient development strategies toward the creation of enterprise, increased income, enhanced gender equity, health, safety and the protection of the physical environment.

The ability to meet, read, and study in an illuminated environment after dark has an enormous impact on the social, economic, physical and spiritual lives of those with limited opportunities for progress. Among the most significant of these benefits are the improved conditions for the education of children and women in areas where poverty and illiteracy walk hand in hand. An additional benefit of fixed or mobile task lighting much valued by end users is the ability to engage in revenue generating activities after dark, including informal cottage industries, and thereby increase household income.

*dirvineh@ucalgary.ca; phone 1 403 220-5941; fax 1 403 282-6855; lutw.org

1.1 LUTW's history

The revolutionary idea of using solid state lighting (SSL) in the developing world was conceived by Dr. Dave Irvine-Halliday in the spring of 1997 after completing a project at the Institute of Engineers (IOE) in Kathmandu, Nepal. With time to spare and his passion for mountaineering, he decided to trek around the Annapurna Circuit in the Himalayas. During the course of the trip he became acutely aware of the lack of safe, healthy and appropriate lighting. The vast majority of rural Nepali homes were illuminated by kerosene wick lamps, resin soaked twigs or candles. In some of the villages there were no teachers and schools also lacked an adequate form of lighting.[1] The suffering experienced by the people because of the use of fuel-based lighting was not something that could be easily ignored!

Back in Canada, being a photonics engineer, Dr. Irvine-Halliday committed himself to find a safe, healthy, efficient and affordable form of "digital" home lighting for the developing world. After years of experimentation, the breakthrough moment occurred when he turned on a white 5mm LED (then newly released by Nichia, Japan) in the darkened photonics lab. In complete darkness, the light produced by a single 0.1 watt white LED (WLED) provided sufficient light for reading. The thought that such a product could allow a child to read at night led to the creation of Light Up The World (LUTW) in the same year.

Since the villagers' average annual income was less that $200USD, while sources of energy were costly, it was clear that the correct decisions regarding the type and level of lighting would have to be made from the beginning: there would be no attempt to illuminate the Nepali village homes to North American levels but instead to provide lighting to those areas of the home where it was of most use. In the years that followed the LUTW Foundation grew from the field-testing of WLED lamps to the installation of entire lighting systems thanks to the generous support of interested individuals, host country organizations, governments, international foundations and industrial partners. To date, more than 5000 homes have been permanently lit up in many countries around the world including: Afghanistan, China, Costa Rica, the Dominican Republic, Ecuador, Guatemala, India, Mexico, Nepal, Pakistan, Peru, the Philippines and Sri Lanka. In addition, the Foundation's SSL systems are being actively tested in field conditions by partner organizations and users in over twenty additional countries.

1.2 LUTW's Mission

The Light Up The World Foundation (LUTW) is a humanitarian initiative whose chief goal is to assist people in remote communities to obtain WLED home lighting that is useful, healthy, reliable, rugged, affordable and environmentally friendly. LUTW also seeks to accelerate the diffusion of SSL technology in developing countries, through research and development, by means of strategic alliances with manufacturers, and by building growth oriented relationships with donor organizations and local entrepreneurs.

For LUTW it is essential that the introduction of solid state lighting to rural communities facilitate expanded access to education – thereby contributing to wider human development – while mitigating the effects of lighting upon the environment by replacing the various carbon-intensive forms of fuel-based lighting.

1.3 LUTW's Vision

LUTW's activities contribute to gender equity and peace: the provision of appropriate lighting to the third of the world's population without access to electricity introduces improved opportunities for education to women and children in particular. By eliminating the health hazards and expenditures associated with fuel-based lighting LUTW contributes directly to the physical and financial well being of communities.

LUTW promotes entrepreneurship and economic growth by facilitating the creation of micro enterprises, while the Foundation also seeks to ensure the diffusion of SSL of the highest quality through its own research and development and by means of strategic alliances with key manufacturers.

LUTW's aim is to contribute in a decisive manner to the realization of the potential for all of the world's underprivileged by the replacement of fuel-based lighting with SSL[2.] For this reason, LUTW works intensively in four main areas: technology evaluation, market development, wealth creation, and diffusion of knowledge and technology.

2. SOLID STATE LIGHTING TECHNOLOGY ASSESSMENT

As part of the commitment to procure the best quality products, LUTW continuously tests, develops and evaluates technology in the fields of solid-state lighting, renewable energy and energy storage at the University of Calgary Solid State Lighting Laboratory (UCSSLL). Ongoing research work performed at the UCSSLL includes white LED lumen output degradation testing, the SSL system performance observation, and the design of efficient driver circuits for dimming white LEDs.

For the experimental results presented below, simplicity, efficiency, lifetime and cost are the main factors taken into consideration. It is a major organizational objective that each product or integrated system that is developed and introduced into the field be consistent with LUTW tenets of sustainable development.

2.1 WLED lumen degradation tests

Under ideal conditions LEDs have the longest lifetime of all artificial light sources. In contrast to conventional light sources, LEDs do not suddenly fail as the bulb ‘burns-out’; instead they present gradual luminous output decay that is related to the driving current and the junction temperature.[3] Moreover, depending on the dye quality, encapsulating epoxy and heat extraction properties, different LED designs will present their own characteristic degradation rates.[4] As can be observed in Figure 1, high flux LEDs (i.e. 1 watt devices), an improved version of their 5mm counterparts, present a dramatically slower decay of luminous output.

The design of the experiment involves a 1 watt high flux white LED or an array of fifteen 5mm WLEDs mounted on a printed circuit board (PCB), which is similar to those used in the lamps already installed in the field. The boards were placed facing up and surrounded by a plastic tube to maintain a constant temperature but that allowed some heat to escape. The ambient temperature was controlled by a room air conditioning system. A constant driving current was maintained at 20 mA and 350 mA for 5mm and high flux diodes respectively. Readings of applied voltage, driving current and luminous output (using an integrating sphere) were taken every 50 and 200 hours for the 5mm array and the 1 watt white LEDs respectively, leading to the following graph:

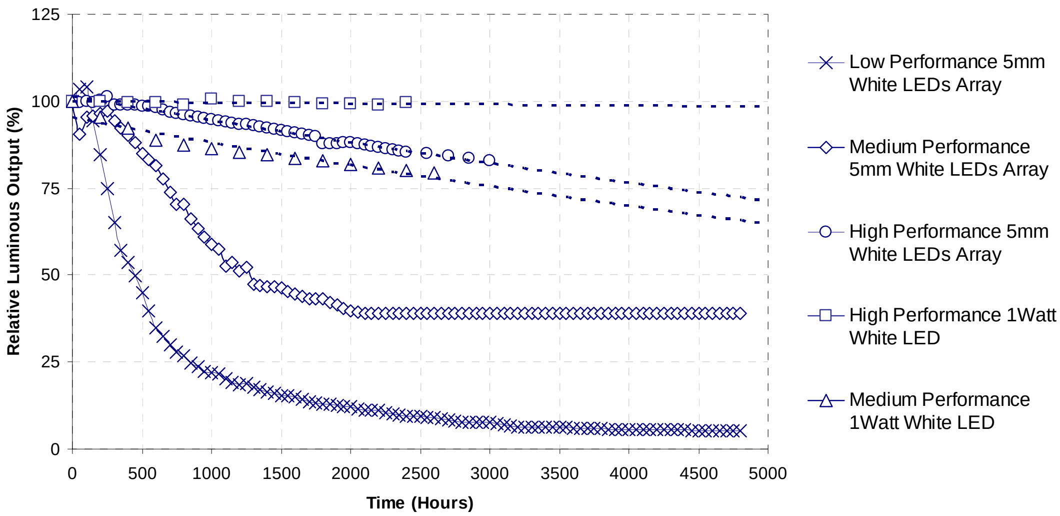
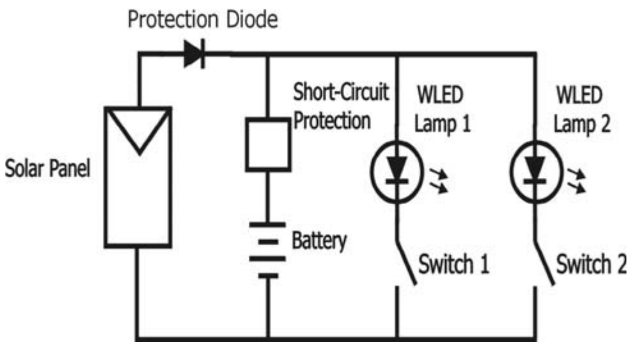


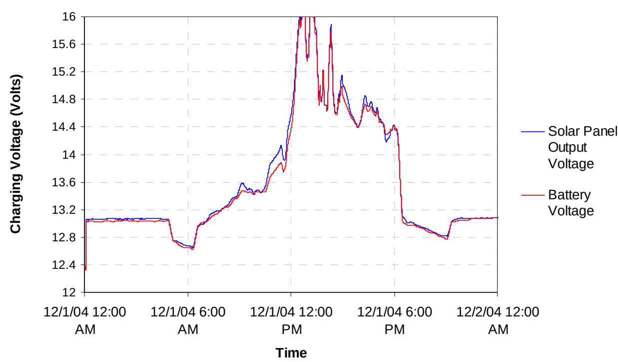
Figure 1: Luminous output degradation for 5mm and high flux WLEDs after continuous operation.

White LEDs demonstrating the best performance are used for the Foundation’s SSL systems, and LUTW’s affiliates are regularly provided with updated experimental results. At present more than a dozen different brands are undergoing testing in the lab.

2.2 Solid state lighting system performance evaluation
The operation of the LUTW's SSL systems using a 5 watt solar panel and a 12 volt 7.2Ah sealed lead-acid battery shown in Figure 2(a) is set up and monitored 24 hours a day. Based on feedback from the field, the lamps are turned on for one hour in the early morning and for three hours in the late evening - see Figure 2(b). Readings of the solar panel output voltage and the battery voltage are taken every minute by a data logger in order to observe their behaviour under different weather conditions and loads. Using this approach it is possible to identify possible causes of failure or elements that can help to improve system performance. Similar experiments are also being run at different latitudes by LUTW's research partners at Kathmandu University in Nepal, and at the University of Colorado in the USA.



(a)



(b)

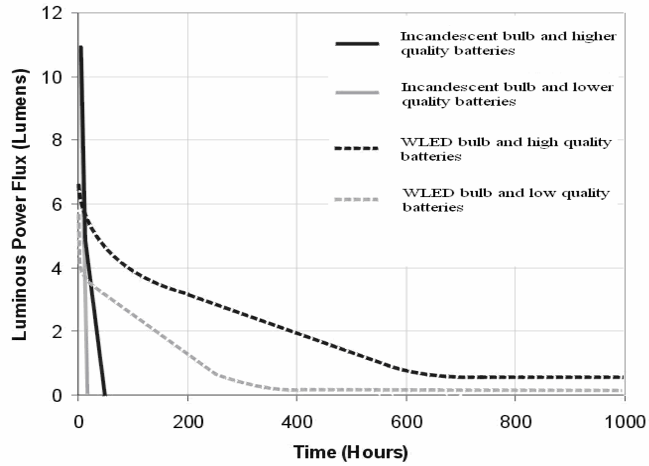
Figure 2: (a) SSL test setup; (b) Solar panels and lighting systems performance plot on data logger screen – May 2005.

2.3 Evaluation of renewable energy sources
In its early days LUTW used pedal generators and pico-hydro generators since at that time the price of other renewable energy sources made them cost-prohibitive. However, following the negotiation of social pricing agreements with manufacturers the use of solar photovoltaic panels for lighting has become possible for many low-income households.

Although LUTW has been using solar panels in recent years, and the UCSSLL continues its research of this technology, a single type of renewable power generation may not be suitable for a particular region. Therefore, joint research into a variety of alternative sources of energy – including wind, hydro, biomass and thermoelectric generators – has been undertaken with LUTW's partners and volunteers at various sites around the world.

2.4 WLEDs in flashlights
The use of white LEDs in handheld flashlights (see Figure 3(a)) can bring enormous environmental and economic benefits to users and their communities alike. From field data it is known that a family in a typical non-electrified home possesses at least one flashlight, and on average the batteries in an inexpensive three "D cell" torch (using an incandescent bulb) would be replaced approximately every two weeks (with the batteries simply thrown away). A conservative estimate that assumes five family members per home suggests that the two billion people currently without access to electricity consume a total of 31 billion "D cell" batteries are every year. This regular expenditure represents an additional drain on villagers' limited incomes.

Most incandescent bulbs are themselves unreliable and may last for only a few days, while many of the batteries they so rapidly consume find their way into the streams and rivers, thereby polluting sources of drinking and irrigation water with all of the concomitant implications for human and animal health. Moreover, for financial reasons – limited cash flows and incomplete market information – villagers more often choose lower cost batteries rather than more durable alkaline batteries. Experimental results, as shown in Figure 3(b), verify manufactures' claims that alkaline batteries last approximately 2.5 times longer than their carbon-zinc counterparts.



(a) (b)

Figure 3: (a) White LED bulb replacements for incandescent bulbs in flashlights, (b) Luminous output comparison of flashlights using a solid-state bulb and a 4.8 W incandescent bulb (commonly found in flashlights) using different batteries.

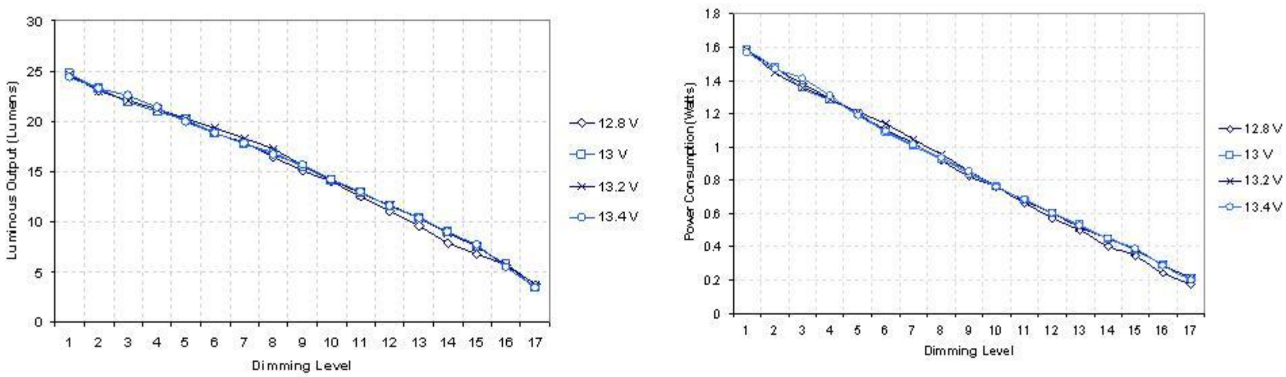
LUTW's three "D cell" white LED flashlight experiments in rural Nepali, Indian and Sri Lankan villages have shown conclusively that the light from a three WLED 'bulb' compares very favourably with that of the typical incandescent bulb version, with a bright light that is truly white rather than yellow in colour. The real advantage however – apart from the WLED 'bulb' being virtually indestructible and lasting for years – is that the batteries in the 3 WLED flashlight provide a *useful* level of light for well in excess of 500 hours, compared to an absolute maximum of 50 hours for the incandescent version. This means that the number of batteries thrown away could be reduced dramatically, an enormous reprieve for the environment. If rechargeable batteries are used then the number of batteries thrown away annually can be further reduced, suggesting that the economic benefits to both villagers and to the environment are simply immense.

2.5 Prototyping of SSL system components

Every lumen of light and joule of energy has a price and an environmental cost, therefore the ideal developing world SSL system and its components has to be simple, efficient and durable. The UCSSLL is constantly prototyping and establishing standards for each of the components used in the LUTW lighting systems. This encourages local self-development of technology in end users' countries and also facilitates the updating of components rather than outright replacement, which produces more waste.

In response to villagers' requests for a soft low power night-light, one of the latest developments is a dimmable white LED lamp prototype. This lamp not only satisfies the initial safety needs but also lengthens the operation time during periods of lower power generation (e.g. cloudy or otherwise inclement weather) as the lamp consumes less power when it is dimmed as it can be observed in Figures 4 (a) and (b).

This LUTW-compatible lamp design can operate from 7.5 to 35 VDC and operates at an electric efficiency of up to 80%. The same driver circuit can power one, two or three 1 watt white LEDs that can also be replaced easily to update the lamp's luminous efficiency.[5] A slightly modified version based on a micro controller allows adding more features such as battery charging – an essential feature for a portable lamp.



(a) (b)

Figure 4: One watt white LED lamp (a) Luminous output and (b) Power consumption vs. dimming level at different supply voltages.

3. TECHNOLOGY DIFFUSION STRATEGIES FOR SOLID STATE LIGHTING

3.1 SSL and technology transfer potential

The transfer and application of environmentally sound technologies is central to sustainable development and poverty alleviation.[6] However, despite major international, national and local initiatives to promote renewable energy technologies in developing countries, the uptake of these technologies has been disappointingly slow.[7] What are the barriers hindering the diffusion of these technologies and what are the solutions to facilitate the technologies' uptake? This chapter will focus on highlighting barriers and identifying strategies for diffusion of SSL technologies powered by renewable energy.

As developing countries continue to modernize, they have the opportunity to select sustainable technologies to meet their energy needs, and thereby avoid a fossil fuel model that is environmentally unsound, inefficient and costly. SSL technologies are environmentally friendly, economically viable, socially appropriate, and have significant advantages over conventional lighting sources.[8] The latest improvements in lighting energy efficiency distinguish solid state white light emitting diodes by an increasing total light output, declining costs per unit of output, and rising efficiencies (lumens/watt).[9] With such rapid improvements in performance it is becoming ever more clear that SSL is the appropriate lighting solution for non-electrified communities in the developing world; one that is both an attractive and a viable alternative to fuel-based lighting currently in widespread use.

There are however a number of barriers that influence the speed and scope of the diffusion of SSL. The synopsis of the select barriers and solutions presented below is based on the existing corpus of literature pertinent to the diffusion of environmentally sound technologies, and also upon the firsthand practical experience of The Light Up The World Foundation's efforts to increase the reach of SSL technology on a global scale. The list is not exhaustive and aims to serve as a starting point in discussions of how best to encourage the proliferation of SSL technologies throughout the developing world.

3.2 Input prices

Energy prices clearly play an important role in the diffusion of energy saving technologies. In a number of developing countries energy is still heavily subsidized.[10] These subsidies create price distortions and discourage energy saving technologies, while such fuel subsidies also divert public funds from important social needs.[9] In India, for example, kerosene and liquid propane gas subsidies are as large as those for education.[9] Removing energy subsidies is an important step in creating incentives for the diffusion of SSL in developing countries.

3.3 Externalities
Under the current economic system, energy prices do not reflect environmental and social costs associated with fossil fuels' production and utilization. Accounting for these externalities through full cost pricing will send an accurate signal to producers and consumers and thus encourage environmentally sound technologies, including SSL.[11]

3.4 Life cycle assessment (LCA)
LCA is an important tool in addressing externalities as it considers the environmental impacts of a product or service over its entire life cycle and helps to identify opportunities to reduce these impacts.[12] Applying LCA to energy products and services permits consumers to make more informed choices about products available on the market, including SSL technologies.

3.5 Regulation
Appropriate use of regulations and market-based incentives can foster investment in environmentally sound technologies, including SSL, and can assist in addressing problems as diverse as:

- Lack of access to appropriate sources of capital
- High or uncertain inflation or interest rates
- High import duties
- Uncertain stability of tax and tariff policies
- Loss of rights to intellectual property and to productive resources
- Risk of expropriation[7]

Empirical research suggests that companies subject to a more stringent environmental regulation are more likely to adopt environmentally sound technologies.[10]

3.6 Capacity building
One of the barriers to SSL diffusion is the lack of human resources and institutional capacity. Key players and stakeholders must be equipped with the necessary knowledge and skills to perform their roles and meet their responsibilities. A high degree of awareness, motivation and empowerment will help public and private sectors and civil society to adapt to a new environment driven by a new technology.[7] Effective and efficient national and regional systems of innovation, research and development should be present.[7] Universities in developing countries can provide a platform for training local specialists and developing the networks and partnerships crucial for capacity building.[13]

3.7 Information systems
Timely access to accurate verified information will be critical in facilitating the diffusion of SSL. A functional information system is important to allow needs and practical challenges to be communicated to those involved in design, development and provision of the technology. This helps to ensure that stakeholders are aware of successes and failures in choosing and applying the technology. Timely access to reliable information is also needed to reduce technology investments risks.[7]

3.8 Financial resources
Lack of access to financial resources is yet another constraint to technology adoption. Development of micro-financing mechanisms, enabling investment policies, as well as internalized costing for other energy products and services will encourage the spread of SSL in the developing world.

4. DELIVERING SOLID STATE LIGHTING SYSTEMS

Delivering solid state lighting systems to the people who are in need in developing countries is a great challenge. Financing acquisition of lighting systems is a major barrier for the diffusion of SSL systems in the developing world. Since its inception, LUTW and its partners have made use of donor contributions in their efforts to provide lighting systems to communities in targeted countries and regions, to obtain invaluable field experience and to develop markets.

Although this donor effort achieved significant success by means of such philanthropic methods, the dependency on donor contributions limited the penetration of SSL systems in poorer regions, and this approach is not sustainable or replicable in the long term. The most direct and efficient way of bringing lighting to the one third of humanity that currently lacks it is by creating an opportunity for them to purchase lighting themselves. This can be achieved by a unified effort of large corporations, local entrepreneurs, government agencies, and financial institutions such as micro-lenders, and non-governmental organizations (NGO). There is a substantial business opportunity for both the larger corporations and local entrepreneurs in the process of providing lighting to the developing world by creating a market for SSL systems for this sector. This market should be identified as a large untapped market segment at the bottom of the economic pyramid (BOP).[14] By bringing in the financial power of large corporations the diffusion of this lighting technology can be made faster and more efficient. Here the question that arises is whether the rural populations in the BOP can afford to purchase lighting systems themselves. Client feedback and data from LUTW projects show they most definitely can if this market is created in a manner optimized for the BOP.

4.1 The buying power of the BOP

The findings of the survey conducted by LUTW in Sri Lanka and the data published at the Proceedings of the Fifth European Conference on Energy-Efficient Lighting, show that lighting is an essential commodity.[15 16]

As shown in Table 1 and also in the proceedings cited above, it is evident that the rural populations spend significant amounts of money to buy kerosene and candles for home illumination.

Findings from the LUTW survey suggest that these amounts are loosely correlated with household incomes.[15] These amounts vary widely from region to region, typically in the range of approximately $20 to $120 per year. Table 2 presents a life cycle costing of an LUTW home lighting system over 10 years and shows that the annualized cost is about $18 at 10% discounting rate, which is clearly affordable for even the lowest spending groups.

Figure 5 shows a simple payback period analysis for different spending groups and one observes that payback is achieved for even the lowest spending group by the fifth year. In addition, the willingness to pay for lighting systems was investigated for all income classes and it is clear that there is a sufficient availability of cash among this sample of the BOP for lighting services.[15]

Currently however, the only option available for lighting is poor quality, hazardous fuel-based products, yet an assessment of the data abundantly demonstrates that an innovative corporation or entrepreneur could provide the option of far superior and safe SSL by tapping into a portion of this existing cash flow that is currently directed towards the purchase of fuel. By doing so, such businesses could not only help members of the BOP to raise their living standards, but could also generate significant profits, given the margins involved and the size of the target market.

Income Group	**Kerosene Expenditure (US$/year)**
Low	18
Medium	18
High	22
Average	19

Table 1: Kerosene expenditure of different income groups in the Knuckles range, Sri Lanka.[15]

4.2 Creating a business to provide SSL to BOP

In order to create a business to provide SSL to the BOP, the unique characteristics of this market should be identified and addressed. Though there is some level of regular cash flow among members of the BOP, it is nevertheless a group with low income and restricted cash flows, and as a result it is not always possible for members of this group to access capital. For example, a very large portion of the income of a farmer is typically generated immediately following the harvest period, leaving the household to manage the remainder of the year on this single month of positive cash flow. It is therefore essential to have in place adequate micro credit options that will permit such households to borrow against future earnings, lease equipment with a view to taking over ownership of the lighting system upon completion of the lease period, or access loans without excessive collateral requirements. Hence, to create an effective SSL delivery mechanism, a unified effort by each of the key parties is needed. The role of each party may be summarized as shown in Figure 6.

Capital Cost		
LUTW Light In a Box Home Lighting System		**$100.00**
Replacement costs		
		PW
Battery at $5	Year 3	$3.75
	Year 6	$2.80
	Year 9	$2.10
Switches and wires at $1	Year 4	$0.68
	Year 8	$0.47
Net present worth (PW) of replacements		**$9.80**
Total life cycle cost		**$109.80**
Annualized cost		**$17.88**

Table 2: Life cycle cost of LUTW for 10 years at 10% discounting rate.

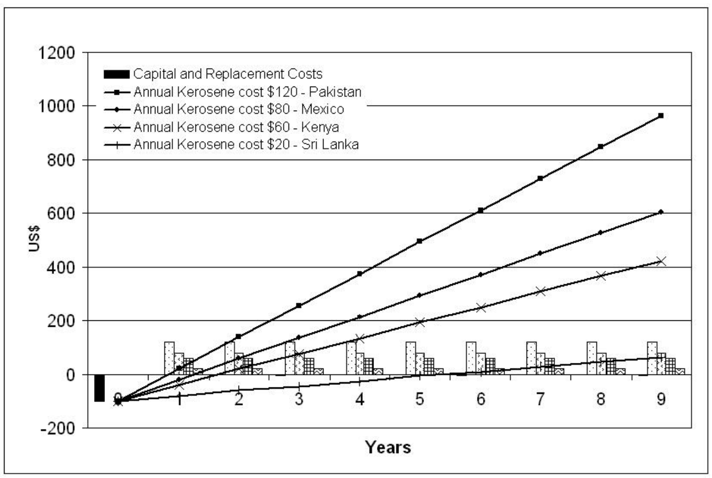


Figure 5: Simple payback period analysis for LUTW home lighting system in selected countries.

4.2.1 Large corporations and local entrepreneurs

These categories play the most important part in the mechanism: a bottom up investment strategy must be adopted and business should be built in a manner that addresses the characteristics of the BOP (e.g. income, market size). Performance and quality of the products must be maintained at high levels, while affordable pricing should be possible by taking advantage of economies of scale, which will be substantial given the enormous size of the market. The BOP must also be treated with respect as in the case of the consumers in the upper tiers of the economic pyramid.

4.2.2 Micro lenders and other financial institutions

The institutions that provide micro credit must work in agreement and collaboration with the corporations as well as with the BOP consumers. Mutual trust must be built between the BOP consumer and the lender, and the ability of the consumer to handle credit must be assessed prior to the provision of any loans. This is as important to the well-being of the client as to the financial institution.

4.2.3 NGOs and civil organizations

In this business model the role of NGOs and other civil society organizations is to act as a facilitating body. Such organizations can create awareness of the advantages of SSL systems vis-à-vis other technologies, provide education and training in the assembly and maintenance of the systems, and also act as an advisor to all parties. An additional key role for NGOs involves coordinating each of the other parties and providing guidance during the important initial phases of model development and product rollout. In this model the NGOs may also be able to obtain donor assistance in order to "jumpstart" the process and help those who are most in need.

4.2.4 Central and local governments

One main task of government agencies is regulation and monitoring of the energy and technology sectors as a whole. Governments can also provide subsidies and tax incentives to the corporations and micro lenders in order to encourage the initial adoption of the sustainable technologies by consumers. These measures can attract multinational corporations such as renewable energy companies, SSL device manufacturers, and financial institutions, all of whose increased activity would strengthen the lighting system delivery structures.

4.3 Evolving roles for the key players

It is clear that both the scale of the demand and the scarcity of donor-based resources calls for a market based model to meet the needs of the BOP. This model calls for innovative investment by large corporations and entrepreneurs to accelerate the pace of SSL adoption; the role of NGOs such as LUTW shifts from donor and manager of projects to a more mature role as technology transfer facilitator and provider of training and guidance to all parties concerned.

This creates a whole new paradigm in SSL marketing and has emerged as the vehicle best suited to providing lighting for the two billion members of the BOP still lacking lighting.

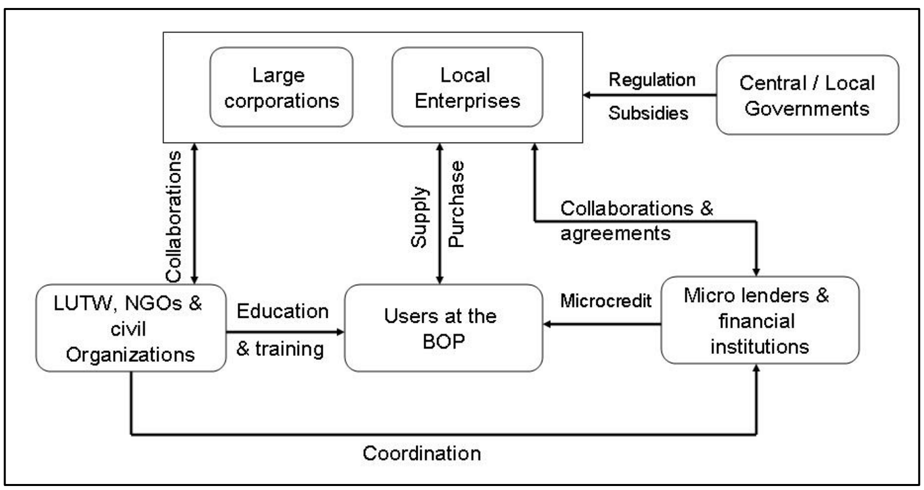


Figure 6: SSL to BOP stakeholder roles

5. CREATORS OF WEALTH

5.1 Life cycle assessment study of different lighting technologies

Based on a model developed by LUTW in 2002, a comparison between different light sources suitable for non-electrified homes is shown in Table 3.[17] As the lighting system is intended to be grid-independent, it is desirable to minimize power requirements to the lowest possible to reduce charging and energy storage station costs (estimated at $1 per kWh).

This slightly modified version adjusts for the prices of compact fluorescent lighting, kerosene costs, and the increases in the luminous efficiency of white LEDs over the last three years. The comparison is based on 50 000 hours, a number that can be attained using the system six hours a day for 20 years – the warranty period for most high quality solar panels, and at which point the top quality white LEDs still retain 70 percent of their luminous output.

This table does not reflect the additional effort (human/opportunity cost) of changing incandescent and compact fluorescent lamps or the inherent ruggedness and portability of SSL (utility).

Kerosene and other non-electric sources of light used in the developing countries are expensive and inefficient. A rural family in the developing world pays the equivalent (over $100 per year in many cases) of what a family from the industrialized world pays for lighting services in order to receive a mere 0.2% of the light services.[9] LUTW is providing its systems at the lowest possible price as a result of long-term social pricing agreements negotiated with component suppliers. Life cycle costing analysis conducted by LUTW suggests that in many cases a rural family can pay back the cost of the SSL system in one to two years. The long life of WLEDs and low power requirements result in extremely low ongoing maintenance costs (rarely exceeding a few dollars a year). As presented in Table 3, cumulative savings from kerosene replacement by LUTW SSL systems (even with systems priced at approximately $100) effectively boost family income. As noted earlier, such improved lighting is suitable for all manner of work and study and therefore also facilitates the establishment of indoor and evening cottage industries helping people earn a modest living.

Parameter	Incandescent	Compact Fluorescent	Luxeon K2 WLED	Kerosene Wick Lamp
Lamp Consumption †	25 W	7 W	1 W	0.05 L/h
Lamp Cost (USD)	$ 1	$ 3	$ 10	$ 1
Lamp Luminous Output (lm)	250	250	60	10
Lamp Lifetime (hours)	1 000	6 000	+ 50 000	5 000
Lamp Lifetime Lumen-hours / $	**250 000**	**500 000**	**300 000**	**50 000**
Lifetime Cost of Lamps	**$ 50**	**$ 25**	**$1 0**	**$ 10**
Lifetime Energy Consumption	**1250 kWh**	**350 kWh**	**50 kWh**	**2500 L**
Lifetime Energy Costs ‡	$ 1250	$ 350	$ 50	$ 1250
Total System Operating Cost	$ 1300	$ 375	$ 60	$ 1260
System Lumen-hours / $	**9 615**	**33 333**	**50 000**	**396.82**
Total System Cost per Lumen	$ 5.2 / lm	$ 1.5 / lm	$ 1 / lm	$ 126 / lm
Lumens per Dollar	0.2 lm / $	0.66 lm / $	1 lm / $	0.008 lm / $

Table 3: Cost comparison between different light sources suitable for grid-independent lighting after 50 000 hours of operation.

5.2 Socio-economic impact

Even with government subsidies the burden of high kerosene costs can represent from 10 to 25 percent of a villager’s annual income. The light output from kerosene lamps is not only low (~ 5 to 15 lumens), it is also very difficult to focus on a specific area for special tasks such as reading; thus, attempts to improve access to education, an essential component of human development, are thwarted. In general, people in rural areas of the developing world who gain more of their income from non-farming related activities are wealthier.§

With the continual improvement in performance and price for LEDs and other SSL system components, a home lighting system consisting of a 5 W solar panel, 7.2 Ah sealed lead-acid battery and two 1 W LED lamps can now be purchased and installed for less than US$100.

The implication for villagers currently forced to use kerosene is obvious: in as little as one year (depending on income

† Consumption given in Watts (W) for Electric lamps and in Litres (L) for Kerosene lamps.

‡ Based on field data, the price of Kerosene is estimated at US $0.5 per litre and the grid-independent energy at $1 per kWh.

§ A similar project that used renewable energy, illumination and micro-credit was the Nepal Solar Village Electrification Demonstration Project (SOVED) and Paper and Power Project, part of the Home Employment and Lighting Package (HELPTM) and current level of kerosene-related expenditures) the cost of a system can be completely paid off, thereafter providing clean, reliable lighting at almost no cost to the owner. Assuming an average villager's home has two kerosene lamps that each consume 0.5 litres of kerosene per week, a family could be paying up to $52 a year if the cost of kerosene rises from $0.50 to $1 per litre.

To accomplish this transition to SSL requires only the establishment of basic micro credit facilities, whereby villagers provide a percentage of the initial price and pay for the remainder on a monthly basis, *substituting the payment for earlier expenditures on kerosene.* Various leasing and similar arrangements can be made to facilitate access to lighting for those lacking sufficient financial resources or collateral.

Upon repayment of the loan or fulfilment of terms of the lease the system is 100 percent owned by the homeowner; thereafter those expenditures hitherto devoted to the purchase of fuel for lighting are liberated for alternative investment. Such savings can be invested in income generating assets, improvements to diet, medical care, education or towards other productive purposes, all of which contribute to the improvement of living conditions for the system owner's household.[18]

5.3 Encouraging social entrepreneurship

Micro enterprise development is a fundamental component of LUTW's philosophy. Conventional project delivery combined with a local business start-up meets the twin demands of reaching very poor sections of the population while simultaneously reinforcing social entrepreneurship as one of the most effective and sustainable forms of local development. Through this approach LUTW ensures that installation, maintenance and support services continue to self-replicate after the initial projects have seeded the technology. LUTW does not own these companies but will assist in their start-up, and in the development of technical expertise and long-term sustainability.

Pico Power Nepal (PPN) which was created in year 2000 by LUTW founder is a successful example of this strategy. PPN operates as a fully locally owned and a independent social enterprise providing affordable lighting systems, installation and warranty services to community members, enhancing income for its operators and providing full-time local employment. Another example, the manufacturing company Crystal Electronics in Sri Lanka, is a local supplier of WLED lamps for the Tsunami Refugee Camp Lighting Project and other local initiatives. Thus over time it has become apparent that LUTW's philosophy of creating micro enterprises also boosts local economic development: by creating a demand for LEDs and solar panels there are also opportunities to manufacture, assemble, and market these products inside the country, thus creating new jobs, and increased industry expertise on a larger scale.

The United Nations Development Programme (UNDP) places electrification, especially in rural areas, as a key factor for sustainable development and the alleviation of endemic poverty.[19] Literacy and education are promoted through the creation of conditions whereby household members are able to read and study after dark. Educated household members are able to develop more advanced working skills, improve their quality of life and make a more meaningful contribution to their community and to their society. On the social side, access to healthy and good quality light may also enrich communities' opportunities to foster cultural development and enhance human relationships.

LUTW also identifies women as benefiting the most after the implementation of solid state lighting. As primary caregivers, women have found that their homes are safer places to raise their children due to better light and the lower risk of fire through the elimination of the kerosene lamp.[20] SSL also alleviates the burden of fuel collection, which takes women and children alike away from educational opportunities and productive domestic activities.[21] "A better educated female population also decreases the infant mortality rate and the fertility rate in the developing world".[22]

6. THE REAL COSTS OF FUEL-BASED LIGHTING

6.1 Toxicity of fuel based lighting

Using a gas analyzer, it was possible to measure concentrations of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) released from a burning kerosene lamp. A probe was placed next to the flame, the lamp was placed on the inside of a 1 cubic metre non-ventilated combustion chamber, and readings were taken every two minutes for ten minutes.

The average concentration measurement of Nitric Oxide was 0.66 parts per million (ppm). This gas easily reacts with oxygen to become nitrogen dioxide (NO_2) with emissions of 3.33 ppm. Due to the severe respiratory conditions that Nitrogen Oxides (NO_x) and Sulphur Dioxide (SO_2) can cause after continuous exposure, the Environmental Protection Agency (EPA) sets a safe maximum concentration level of 0.053 ppm for NO_2.[23]

SO_2 emissions reached 17 ppm, whereas the EPA sets a maximum concentration level of 0.03 ppm for this gas. Hazardous Volatile Organic Compounds (VOCs) are also released, representing 0.26 percent of all the gases produced by the combustion of kerosene.

Nevertheless, these released gases may pose less of a danger compared to carbon monoxide (CO), which has no colour or smell and whose presence in high concentrations (~3200 ppm) can kill a person in a few minutes. Even in low concentrations (~200 ppm), CO reduces the amount of oxygen delivered to the body's organs affecting the central nervous system causing dizziness, vision problems, fatigue, memory loss, and diminished dexterity and concentration. The measured concentration for carbon monoxide was 677.33 ppm.

Kerosene lighting is also responsible for significant Carbon Dioxide (CO_2) emissions. Even though this gas does not have a direct impact on humans it is the main contributor to global warming. It is estimated that 244 million metric tonnes of CO_2 are released every year due to kerosene-based lighting.[24] This amount represents 3.25 percent of the total global CO_2 emissions (~ 7.5 billion metric tonnes) but equates to 13 percent of the total CO_2 emissions from lighting globally.

From field experience it is known that a typical low income non-electrified home consumes one litre of kerosene per week with annual CO_2 emissions reaching 133.9 Kg. Therefore each home replacing kerosene-based lighting by electric light sources using renewable energy would virtually eliminate a ton of CO_2 emissions every seven and a half years. If carbon credits were a reality and the trading price for each ton of CO_2 was $30 USD, SSL would be the only illumination alternative that could pay itself off during its useful lifetime.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 A market for the future

Few markets can possibly possess the growth potential of the SSL market that LUTW has begun to develop. It has been noted that more people today lack access to electrical lighting than the entire global population of Edison's time.[9] With the number of households lacking access to electricity growing throughout the developing world, there is a both a window of opportunity for environmentally benign technology to flourish and for business to offer solutions to those most in need in an altogether underserved market.[9]

At present the unrelenting and ever increasing worldwide demand for LUTW's assistance is such that it is stretched in its capacity to respond meaningfully to every appeal for assistance; thus creating a market opportunity. "The need is there, the solution is there; only more hands are needed."

7.2 The potential of SSL as a catalyst for change in the developing world

With the introduction of SSL to the global market the relationship between supply and demand of lighting energy has unquestionably changed forever.

The absolute magnitude of the home lighting energy requirements of even the poorest nations are mind bogglingly large, and therefore it behooves us all to collectively find ways of meeting these needs while optimizing the use of existing energy supplies. It is estimated that 25 to 30 percent of the world's total electricity production is consumed by lighting. It is imperative that we use the most energy-frugal forms of lighting available, particularly in the developing world, where demand is growing at an accelerating rate as a product of economic development. The fewer power stations constructed to meet the needs of lighting, the fewer emissions and waste generated, and the more capital available for other investment. "A power station not built is a good power station." In the current environment, rising energy costs place further pressure on consumers and government alike, both of whom benefit enormously from mitigation of demand.[25]

7.3 The ongoing search for solutions

The Light Up The World Foundation was the first humanitarian organization to introduce the liberating technology of solid state lighting to homes in the developing world, and it continues this leadership in its efforts to introduce solid state lighting to those most in need.
The greatest challenge is to meet the demands of its market in a tangible way, a market that is enormous and continues to grow as a consequence of population growth.

To achieve this ambitious goal LUTW focuses on establishing partnerships with industry and social organizations in order to:

1) Drive down the cost of its solid-state lighting solutions through innovative designs and preferential supply chain relationships, and;
2) To plug into effective delivery mechanisms that can coordinate and administer LUTW affiliated projects worldwide.

A further challenge to be addressed is in the development of performance metrics, particularly lifecycle measures of cost effectiveness and life cycle environmental impact assessment, both of which are critical in permitting researchers and policy makers make meaningful comparisons of LED systems vis-à-vis existing conventional lighting technologies.

ACKNOWLEDGMENTS

The authors would like to express their most sincere gratitude to the following organizations:

- The Natural Science and Engineering Research Council of Canada (NSERC)
- CONACYT (Mexico)
- The Department of Electrical & Computer Engineering, Schulich School of Engineering, University of Calgary

REFERENCES

1. D. Irvine-Halliday and S. Craine, “Does the Overdeveloped World Appreciate the Win-Win-Win Opportunities for HBLEDs in the Developing World?”, *Light Emitting Diodes 2001*, San Diego, 2001.
2. S. Craine, W. Lawrance and D. Irvine-Halliday, “Pico Power: Lighting Lives with LEDs”, *Australasian Universities Power Engineering Conference* [CD-ROM], Melbourne, 2002.
3. Y. Gu, N. Narendran and J.P. Freyssinier, “White LED performance”, in *Fourth International Conference on Solid State Lighting*, I.T. Ferguson, N. Narendran, S.P. DenBaars, J.C. Carrano, ed., *Proc. SPIE* ***5530***, pp. 119-124, International Society of Optical Engineers, Bellingham, 2004.
4. Y. Gu and N. Narendran, “A non-contact method for determining junction temperature of phosphor-converted white LEDs”, in *Third International Conference on Solid State Lighting*, I.T. Ferguson, N. Narendran, S.P. DenBaars, J.C. Carrano, ed., *Proc. SPIE* ***5187***, pp. 107-114, International Society of Optical Engineers, 2004.
5. R. Peon, “Solid State Lighting Systems: A brighter future for the developing world”, Master’s thesis, Faculty of Graduate Studies, University of Calgary, Calgary, 2005.
6. Unites Nations (UN), *Agenda 21: Programme for Action for Sustainable Development*. UN, New York, 1993.
7. United Nations Environmental Program (UNEP), *Technology Transfer: The Seven “C”s for the Successful Transfer and Uptake of Environmentally Sound Technologies*, UNEP, Osaka, 2003
8. R. Peon, D. Irvine-Halliday and S. Leon. “Solid State Lighting for Developing Countries.” *World Renewable Energy Congress VIII* [CD-ROM], Denver, 2004.
9. E. Mills, “The Specter of Fuel-Based Lighting”, *Science* **308**, pp. 1263-1264, 2005.
10. A. Blackman, “The Economics of Technology Diffusion: Implications for Sustainable Development,” *Issue Brief*, pp.02-24, 2002.
11. D. Thompson, Professor of Environmental Science, Faculty of Environmental Design, University of Calgary. Personal Communication, Winter 2005.

12. A. Higgins and D. Thompson. “Life Cycle Assessment,” in *Tools for Environmental Management*, D. Thompson ed., pp.293-305. New Society Publishers, Gabriola Island, BC, 2002
13. B. Gordon. “Capacity Building in Universities: Strengthening Environmental Science and Management Programs,” Master’s thesis, Faculty of Environmental Design, University of Calgary, Calgary, 2004.
14. C. K. Prahalad, *The Fortune at the Bottom of the Pyramid, Eradicating Poverty Through Profits*, Wharton School Publishing, Upper Saddle River, 2005.
15. S. Leon and S. Graham, "Village Lighting in Sri Lanka: Socio-Economic Impact Evaluation of LUTW Solid State Lighting (SSL) Technology", Social impact assessment report, Light Up The World Foundation, Calgary, 2005.
16. E Mills, "The $230-billion Global Lighting Energy Bill," *Proc of the Fifth European Conference on Energy-Efficient Lighting, International Association for Energy-Efficient Lighting*, pp. 368-385, Nice, 2002.
17. K. Robertson, S. Crane, D. Irvine-Halliday and R. Stone, “SSL for Human Development”, *Light Emitting Diodes 2002*, San Diego, 2002.
18. M. Fafchamps and A.R. Quisumbing, “Human Capital, Productivity and labor allocation in rural Pakistan,” *The Journal of Human Resources*, **34**(2), pp. 369-406, 1999.
19. United Nations Development Programme (UNDP). www.undp.org – April 2004
20. D. Green, “Thailand's solar white elephants: an analysis of 15 yr of solar battery charging programmes in northern Thailand”, *Energy Policy*, **32**(6), pp. 747-760, 2004.
21. UNDP Thematic Trust fund: Energy for Sustainable Development, 2005 [Online], Available: http://www.undp.org/trustdunds/energy-english-final.pdf
22. P. Glewwe, “Why Does Mother’s Schooling Raise Child health in Developing countries? Evidence from Morocco” *Journals of Human Resources*, **34**(1), pp. 124-159, 1999.
23. U.S. Environmental Protection Agency, See: http://www.epa.gov, (February 2005)
24. Intergovernmental Panel on Climate Change, http://www.ipcc.ch/ - Nov, 2003
25. R. Peon, I. Platonova, G. Doluweera and D. Irvine Halliday, ”Solid State Lighting”, in *Renewable Energy Solutions, Handbook for Developing Countries*, L. Engvall, ed., ch. 4.10, ITU-D, 2005.