4.10 Solid State Lighting

D. Irvine-Halliday, R. Peon and I. Platonova

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

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Dave Irvine-Halliday, MSM, PhD, PEng, Rodolfo Peón, BSc(Eng), Inna Platonova, MA
Light Up The World Foundation,
University of Calgary

4.10.1 Introduction

Recently adopted by International Illumination Engineering Societies, the term Solid State Lighting (SSL) is used to describe of the use of White Light Emitting Diodes (WLED) for illumination purposes. Prior to the employment of semiconductors, almost every active electronic circuit used fragile vacuum tubes [1]. Therefore the title ‘solid state’ is derived from the use of solid pieces of semiconductor material in the constitution of LEDs, the source of illumination.

The seed for LEDs was planted throughout the experiments of Henry J. Round, who in 1907 reported light emission by applying high voltages to silicon carbide crystallites – a material commonly found in sand paper [2]. It took decades to understand the quantum physics behind semiconductors in order to develop effective SSL technologies.

The first practical commercial diode which emitted a low red light was invented in 1962; yellow, orange, green and blue LEDs appeared after. It was not until 1996 that the first WLED was developed. Pioneered by Shuji Nakamura and Gerhard Fasol, the process of combining blue emission with a down converting phosphor layer is still the most commercially advantageous method to achieve white light [3].

LEDs are being widely used in industrial applications, including public and commercial signage, signaling, and automotive sector. Recently developed WLEDs bring significant benefits over conventional light sources and are becoming a suitable lighting source for general illumination.

WLEDs are safe, reliable, physically robust, energy efficient, cost effective and environmentally friendly. A single ‘0.1 Watt’ WLED offers enough light to allow reading in the dark [4]. There is no question that SSL powered by renewable energy is an ideal solution to the remote non-electrified communities. SSL has a huge potential to improve the quality of life of the 2 billion people currently without access to a safe, healthy and affordable light [5].

4.10.2 Technical Description of Light Emitting Diodes

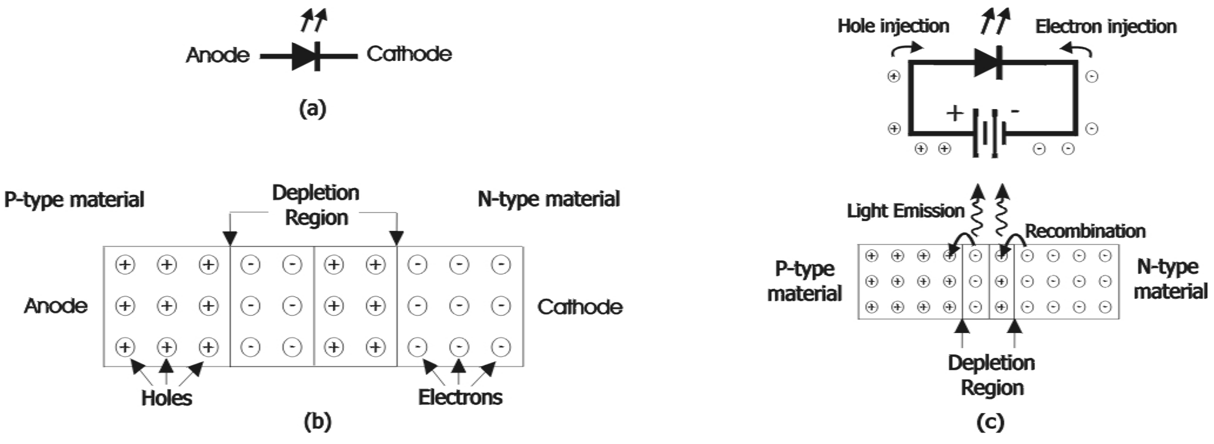
In essence, an LED consists of the junction of P-type and a N-type semiconductor materials. Represented by the symbol shown in figure 4.10.1(a), the anode and the cathode stand for the P-Type and the N-Type materials of the semiconductor junction respectively. As can be observed in figure 4.10.1(b) the N-type region has electrons in excess whereas the P-type region has an excess of holes – spaces that can be occupied by electrons [6, 7].

When N-type and P-type materials are put together, electrons and holes merge together creating an electrically neutral zone between both regions. This electrical barrier can be significantly enlarged or reduced by applying a ‘reverse’ or a ‘forward’ external bias respectively.

On the other hand electrons can only occupy discrete levels or states of energy, also called the energy bands. In an atom, the energy difference between the last occupied band (*the valence band*) and the lowest empty band (*the conduction band*) is known as the *band gap*.

Light emission occurs in a forward biased diode when injected minority carriers (electrons in the cathode region and holes in the anode region) recombine between them. During this process, free electrons fall from the conduction band to the valence band (a lower energy level); the energy balance is then maintained by the generation of a photon [2]. As shown in figure 4.10.1(c), the electron-hole pairs’ recombination happens in all regions. This phenomenon known as electroluminescence is the principle of operation of all LEDs [3].

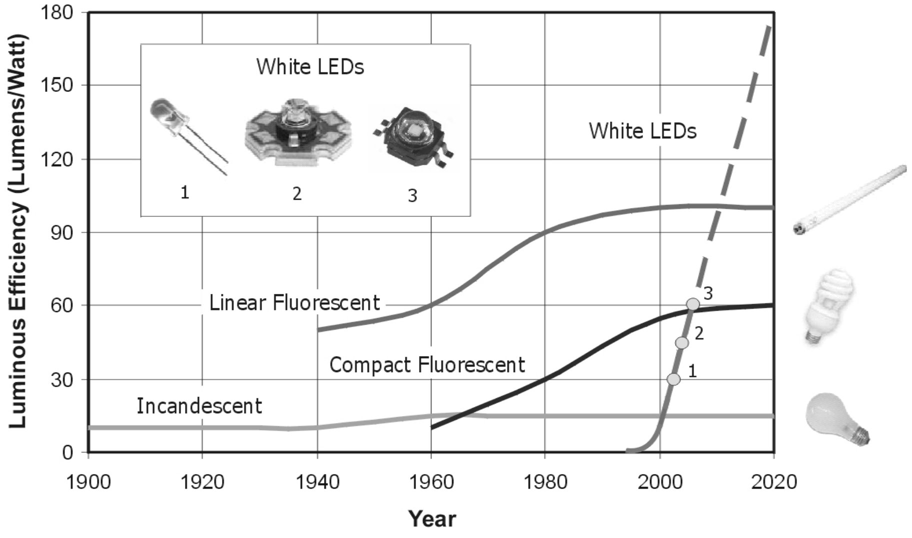
Figure 4.10.1: (a) Electronic Symbol of LEDs, (b) Cross section diagram of p-n semiconductor junction, and (c) P-n junction under forward bias.



LEDs come in a variety of sizes and shapes, but probably the most common one is the 5mm or T1¾ which is shown in figure 4.10.2, and has been used for decades as an indicator lamp. Regardless of their light emission color (wavelength in nanometers) and luminous flux (in lumens), all LEDs consist of three essential parts:

1. Semiconductor junction (or LED chip), where the light is produced,
2. Encapsulating epoxy which acts as a lens and protects and extracts light from the chip and
3. Connection terminals which also serve as heat dissipaters for conventional LEDs only.

Figure 4.10.2: Lighting technology evolution comparison including different Solid State Lighting Devices



(1) 5mm WLED introduced by Nichia Corporation of Japan in 1996,
(2) Luxeon Star – the first high-flux WLED in the market developed by Lumileds, USA
(3) Luxeon K2 – the brightest device up to date (also developed by Lumileds).

Source: Lumileds

As the luminous flux of LEDs keeps increasing, it will be necessary to develop more effective heat extraction properties as temperature plays a very important role in their performance and eventually in their lifetime [8].There are several types of encapsulation for commercial high-flux LEDs which allow much higher driving currents and superior heat dissipation from the chip. One of the most efficient designs up to date, the 'Luxeon' has been developed by Lumileds.

As it can be observed in figure 4.10.2, the luminous efficiency of WLEDs is continuously improving and in the next decade the efficiency of SSL is expected be significantly higher than that of fluorescent lighting. This will not only benefit people without access to electricity but also SSL will play a key roll in energy savings – thus becoming the lighting technology of the third millennium.

4.10.3 Driving LEDs

One of the biggest advantages of LEDs is their simplicity of use. There are several easy ways to develop a reliable driver circuit. The baseline is to perform current regulation and to protect LEDs against reverse bias. Current regulation is preferred over voltage regulation for mainly three reasons:

1. The forward current rises exponentially for a small increase of the forward voltage. Deviations of the operating voltage may exist between LEDs, even though they come from the same batch. Therefore a constant voltage might lead to significantly different driving currents.

2. The operating voltage also varies as ambient temperature changes. Hence, any fluctuation of the ambient temperature could again mean an alteration of the driving current. In both cases LEDs may be overdriven, thus reducing their lifetime.

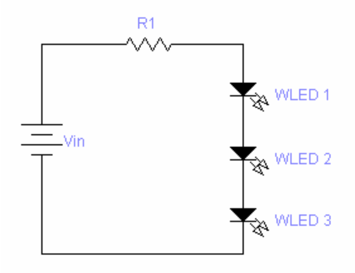
3. Neglecting the temperature changes, the driving current and the LED luminous output relation is practically linear. Therefore to maintain a constant light intensity, more precise control is achieved with current regulation than with voltage regulation.

LEDs work on Direct Current (DC). Nevertheless, they can also be run with Alternate Current (AC) and under Pulse Width Modulation (PWM). For the design of driver circuits analyzed below the operation under a constant DC power supply is considered.

Resistive LED Driver Circuit

An array of diodes connected in series to a DC supply through a current limiting resistor is the simplest way to drive them. As can be observed in figure 4.10.6, a lamp using this technique requires a few components that are inexpensive and widely available around the world.

Figure 4.10.6: Simple series resistor LEDs driver circuit



This topology can offer very high electric efficiencies (above 80%), especially when the total voltage drop across the LEDs array closely matches the power supply voltage. In this case a very small resistor is needed, where some power is wasted. Hence, virtually every watt consumed is used by the LEDs for the production of light. The design of a resistor-based LED driver circuit (LDC) comprises the following steps:

- **Obtaining the average operating voltage at which LEDs run at the desired current**. In practice this value is within the range from 3 to 4 volts depending on the brand used; manufacturers usually provide this information on their spec sheets.

- **Determining the number of LED per array.** Dividing the power supply voltage by the LEDs' average operating voltage the maximum number of LED per array can be obtained.
- **Calculating the current limiting resistor.** Using Ohm's law, $I = V/R$, where I is the forward current, V is the voltage drop across the resistor element, and thus the resistance R of the element can be found.
- **Choosing the Power rating of the resistor element.** Denoted by P, the power consumed by the resistor element is given by the expression $P = I^2R$.

High-flux LEDs can be driven using this design as well; however high power resistors may be needed if the element is above a couple of ohms. This would represent a higher power waste and thus a low efficiency performance. In that case, switched mode operation could be more suitable.

Switched-Mode LED Driver Circuit

A switched-mode DC/DC converter (analogous to an AC transformer) is very effective when power has to be adapted and maintained at specific values of voltage or current – either above or below that delivered by the power source. There are several types of DC/DC converters, but probably the most commonly used for driving LEDs is the Buck or down converter. This topology is only appropriate when the source voltage is higher than the required for the device.

A Buck converter consists essentially of a switch between the source and the load which opens and closes at a constant frequency. The ratio of the on-time to the switching period is the duty ratio, which can be width-modulated to control the power transfer to the load [9, 10].

The combination of the switching elements and the ripple filtering components results in the constitution of the DC/DC converter switching cell. As a practical example, the design process of a simple Buck driver circuit for a high-flux 1 Watt WLED is discussed below:

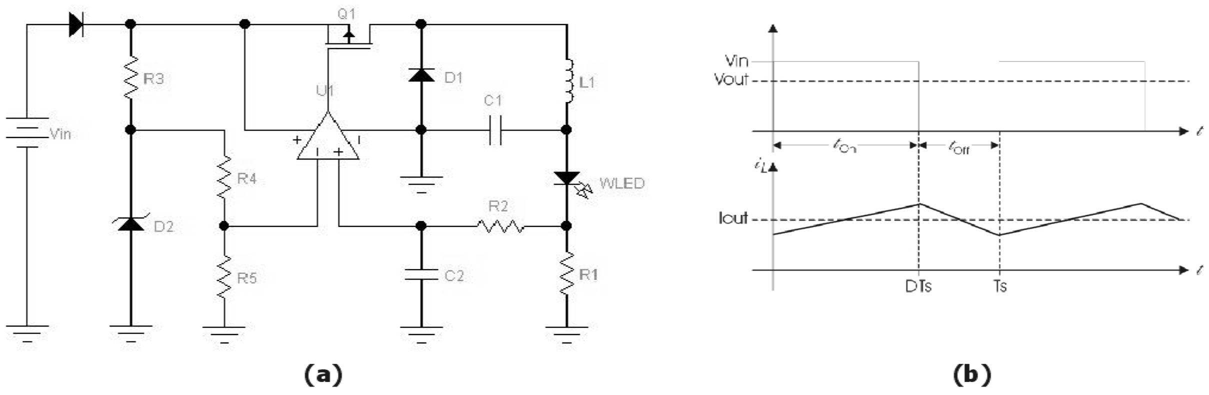
- **Choosing the switching frequency.** Usually the manufacturer specifies an appropriate switching frequency. A switching frequency beyond the human audible region (20 Hz - 20 kHz) is recommended to avoid the perception of the humming noise associated with the inductor.
- **Determining the ripple-filtering elements.** The ripple can be reduced by making the filter elements large; however the cost will increase. If small inductors and capacitors are used, a higher switching frequency is necessary.
- **Choosing the switching elements.** Components offering low power losses and fast switching response are the most suitable for this purpose.
- **Feedback and PWM control.** A current sensing element and a reference resistor passed through a low power consumption comparator, represents an optimum and reliable solution.

When the circuit, see figure 4.10.7, is connected to a power supply, a current starts to flow through the load until it is high enough to generate a voltage drop across R_1 comparable with the reference voltage at D_2. At this point the comparator output goes to positive saturation (equivalent to the input voltage) thus turning off transistor Q_1. Then, some of the stored energy on the inductor L_1 is transferred to the load throughout the freewheeling diode D_1.

As the current drops, the voltage across R_1 decreases as well placing a lower potential than the reference voltage at the non-inverting terminal. Hence, the comparator output goes to negative saturation (equivalent to ground voltage) thus turning on transistor Q_1 again. This process is repeated while the circuit is powered while the switching frequency is given by the time delay created by R_2C_2 elements and the switching speeds of transistor Q_1 and diode D_1.

More LEDs can be driven using this topology, as long as the total voltage required by the series array is lower that the input voltage, and that the switching elements can handle the demanded current. There are several commercial switch-mode regulators that can be also used to drive LEDs. The vast majority present very high electric efficiencies but have limitations for the driving currents. A high performance Buck converter can offer electrical efficiencies above 80%.

Figure 4.10.7: (a) Buck converter LED driver circuit, (b) Voltage and Current waveforms.



4.10.4 Grid-Independent Solid State Lighting System

A third of humanity is not connected to a grid and the majority may not be connected to the grid in the foreseeable future, therefore grid-independent solutions must be pursued. As every joule of stored energy and every lumen of emitted light have a price and an environmental cost, the design of a grid-independent lighting system has to be simple, reliable, efficient and low cost. WLEDs powered by renewable energy represent an optimal lighting solution to off-grid rural communities.

Table 4.10.1: Operational cost comparison between different light sources suitable for grid-independent lighting – 50,000 hours operational time

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 / $**

* Consumption given in Watts (W) for Electric lamps and in Liters (L) for Kerosene lamps.

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

Source: LUTW, 2002, 2005

Table 4.10.1 compares different lighting systems and shows that WLEDs have significant advantages over conventional lighting sources. The calculations are based on 50,000 hours of operational time, which is equivalent to 6 hours of the system operation per day for 20 years (regular warranty period for high quality solar panels). This table does not reflect the additional effort (human cost) in charging incandescent and compact fluorescent lamps or the inherent ruggedness and portability of SSL.

To design a grid-independent SSL system, the following steps are recommended.

- **Determine required illumination levels.** According to the North American Illumination Engineering Society standards, an appropriate level of illumination for task lighting is between 300 and 1000 lux and for simple orientation is between 30 and 100 lux [11].
- **Obtain optical power of LEDs.** This information is usually provided by the LEDs' manufacturer either in lumens or in milicandelas. It is also important to observe the beam characteristics in order to decide if external optics are needed to focus or diffuse the light.
- **Design driver circuit.** The driver circuit should be as efficient as possible to reduce power losses while achieving desired illumination levels. In order to prevent the battery from being overdischarged, a low voltage cut-off circuit should be incorporated into the driver.
- **Determine the battery capacity**. It has to be able to be charged in one day and allow the full operation of the lighting system for a minimum 4 hours a day. If desired, a certain number of days of recharging independence can also be considered.
- **Battery protection**. Short circuit protection of the battery should be an integral part of the SSL system.
- **Determine the energy source.** The low power consumption of LEDs not only makes for an inexpensive energy storage unit but also gives more chance for different types of renewable energy to be used. Depending on the location, and the annual average weather conditions, the energy source can include solar, wind, hydro, human or animal, thermoelectric, electro-mechanic, biomass or various combinations.

4.10.5. Light Up The World Foundation – SSL for Human Development

LUTW Foundation (LUTW) is an international humanitarian organization dedicated to illuminating the lives of the world's poor. It is the first humanitarian organization to utilize SSL technologies to bring affordable, safe, healthy, efficient, and environmentally friendly lighting to people currently without access to proper lighting. LUTW remains the world's leader, globally active and setting standards in this field.

LUTW lighting system (See Figure 4.10.8a) consists typically of:

- two 1 Watt WLED lamps
- one 12 V, 7.2 A-h Sealed Lead-Acid rechargeable battery
- one 5 Watt solar panel

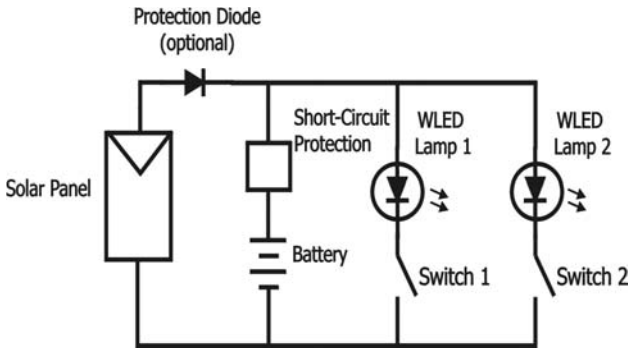
LUTW only uses top quality WLEDs provided by Lumileds (USA) and Nichia (Japan).

The LUTW lamps using the 1 Watt Lumileds Luxeon WLED have an electronic driver circuit, which keeps the output luminous flux at a constant value virtually regardless of variations in the input voltage. They also have protection against reverse voltage polarization and their low voltage cut off feature extends the lifetime of the batteries to approximately 5 years. The high quality solar panel's lifetime is guaranteed by the manufacturer to be at least 20 years.

LUTW lamps, each using nine 5mm Nichia WLEDs have also been successfully used for many years [4]. The dimmable lamps for the ongoing Tsunami Refugee Camp Lighting Project in Sri Lanka use fifteen Nichia WLEDs (See Chapter 9.8).

Figure 4.10.8: (a) LUTW's Solid State Lighting System, (b) Schematic Diagram of Grid Independent Solid State Lighting System

(a)



(b)

Source: LUTW

LUTW developed a comprehensive installation manual which provides detailed instructions regarding installation, operation and maintenance of the SSL system [12].

New features have been developed for the lamps such as focusing and dimming, in order to make them more versatile. The focusing capability enables the lights to change from a room light to a task lamp. The dimming property saves energy and also makes the lamps a comfortable night light [13].

Since inception, together with implementation partners and with generous support from interested individuals, host country organizations, governments, international foundations and industrial partners, LUTW has lit up more than 5,000 homes in numerous countries including Afghanistan, Bolivia, China, Costa Rica, Dominican Republic, Ecuador, Ghana, Guatemala, India, Mexico, Nepal, Pakistan, Peru, Philippines, Sri Lanka and Zambia. Over 25,000 people have been impacted directly. At least another 3,000 homes are to be lit this year as part of Sri Lanka Tsunami Refugee Camp Lighting Project.

Through promoting SSL technology LUTW is addressing socio-economic and environmental problems on both a regional and global scale. The beneficiaries are the rural communities who have no access to adequate lighting. The benefits of WLED lighting technology become most evident with significantly improved living conditions, enhanced safety and health conditions, improved environment, ability to read and study after sundown and operate a cottage industry by night [5, 14].

Health & Safety

The effects of fuel-based lighting are serious and debilitating for the developing world. Being a primary lighting fuel, kerosene causes heavy local and indoor air pollution resulting in illnesses and death. Acute respiratory infections such as influenza and pneumonia kill nearly 2 million children in developing nations each year [15].

Kerosene lamps and candles are also responsible for countless fire catastrophes every year. In India alone, 2.5 million people (350,000 of them children) suffer severe burns each year, primarily due to overturned kerosene lamps. Each year, many homes burn to the ground when a lamp is toppled [15].

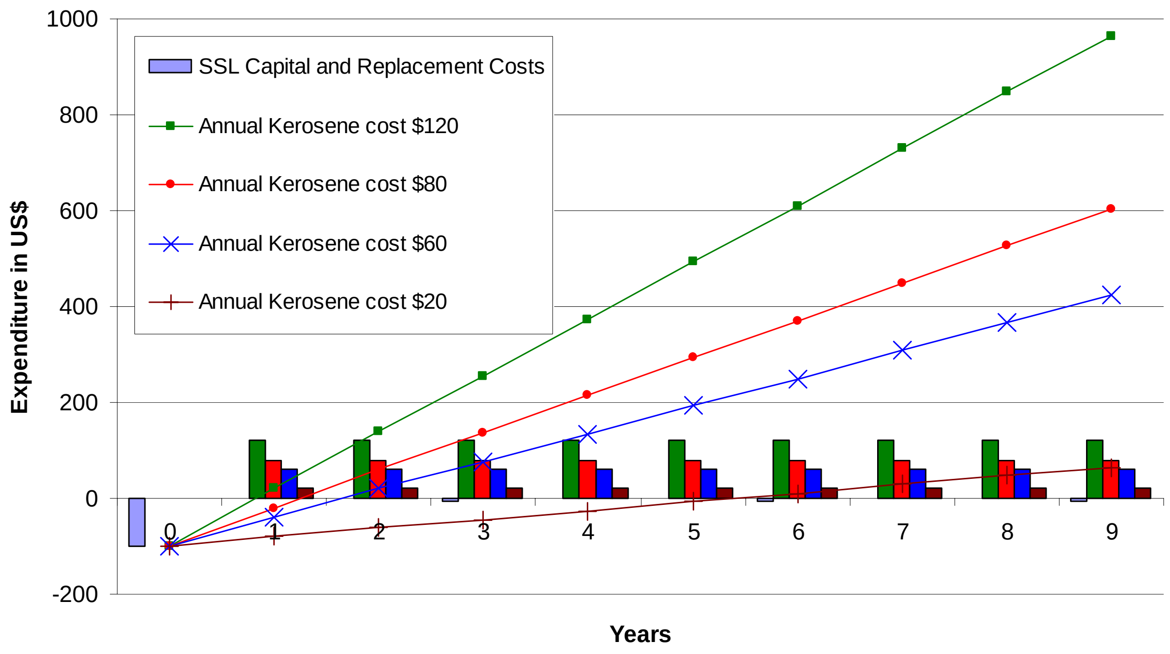
Safe, reliable and near permanent WLED lighting provided by LUTW reduces air pollution in the home enhancing safety and improving health conditions. Each village where kerosene lamps were replaced with LUTW systems has reported significant improvements of air quality in their homes. Mobile WLED lighting has also allowed safe field access after dark [16].

Economic Development & Poverty Reduction

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 only 0.2% of the light services [17]. LUTW is providing its systems at the lowest possible price as a result of long term social pricing agreements negotiated with the 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 1-2 years. The long life of WLEDs and low power requirements result in extremely low (few dollars a year) ongoing maintenance costs.

As presented in Figure 4.10.9, cumulative savings from kerosene replacement by LUTW's SSL (systems priced at approximately $100) significantly boost the family income. Lighting also facilitates the establishment of indoor and evening cottage industry helping people earn a modest living.

Figure 4.10.9: Payback Period Analysis for SSL Systems



Source: LUTW

By promoting the use of renewable energy LUTW is helping to divert national funds away from the consumption of fossil fuels. It is estimated that fuel-based lighting is responsible for energy consumption of 77 billion liters of fuel per pear at a cost of $38 billion/year. This equates to 1.3 million barrels of oil per day, comparable to the total production of Indonesia, Libya, or Quatar, or half that of prewar Iraq [18]. Energy costs divert money away from food, health services, housing and other basic needs in developing countries. Moreover, for a country like Nepal that spends one third of its GDP on imported kerosene and distribution subsidies, fluctuations in world energy markets affect the country's holding of valuable foreign currency. The opportunity in economic terms of moving away from fossil fuel imports is enormous and frees up foreign exchange for national programs.

Local Business Opportunities

Microenterprise 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 a very poor segment 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 replicate after the initial projects have seeded the technology. LUTW does not own any of these companies but will assist in their start-up, development of expertise and sustainability [14].

Pico Power Nepal (PPN) is a successful example of this strategy. PPN operates as an 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. Crystal Electronics, a manufacturing company in Sri Lanka, is a local supplier of WLED lamps for the Tsunami Refugee Camp Lighting Project and other local initiatives.

Literacy and Education

Inadequate lighting affects literacy and education. The light output of kerosene lamps is very low and children can only see their schoolbooks if they are very close to the lamps thus directly inhaling the toxic smoke [15].

The ability to read and study after sundown has an enormous impact on the lives of those with little opportunity. Not the least of these benefits is the improvement in education of children and women in areas where poverty and illiteracy walk hand in hand. Education leads to a *people centered development* – a knowledgeable population that can strive for better lives.

Equality

In many developing countries, women must assume the bulk of the productive, reproductive and community organization roles but have limited political power and social status. Adding to their responsibility, women in many rural non-electrified communities spend several hours a day scouring the landscape for scarce firewood. Others may trek for days to reach the nearest kerosene depot only to find that no fuel is available or it is too expensive. LUTW works to address these issues by using SSL as a community development tool in areas where inequality, poverty, and illiteracy are a complex problem.

4.10.7 Environmental Savings

Simply replacing the incandescent bulb with a three 5mm WLED bulb will extend the battery life by at least a factor of 10, thus it is not only a creator of wealth but also saves the environment. Furthermore by substituting the use of dry-cell batteries with rechargeable batteries, fewer batteries have to be disposed, thus reducing the release of heavy metals into the local environment. In Nepal, a country with over 24 million people, literally hundreds of millions of non-rechargeable batteries are discarded directly into the environment each year [19]. The resulting pollution to streams, groundwater and fields threatens to be immense.

Similarly, the installation of WLEDs reduces the demand for firewood and as a result diminishes the negative impacts on landscapes, such as deforestation and desertification. According to the United Nations the primary cause of habitat destruction and run-off water pollution is the denudation of the landscape by the rural poor in a desperate search for scarce firewood. By various estimates from the Schumacher Institute and other development organizations, 60%-90% of firewood and fuel use is for lighting purposes.

Furthermore, LUTW is also very active in remote rural areas that are ecologically sensitive. In 2003 LUTW's lighting systems contributed to the preservation of the biologically diverse Knuckles Range, a proposed UNESCO World Heritage Site and nature reserve in Sri Lanka. Protection regulations preclude the inhabitants from being connected to the electrical grid. Together with partners, LUTW has provided leading edge lighting technology to many villages. LUTW has committed to lamping the remaining villages in the Knuckles Range in 2005 and has commissioned a study to analyze the social and economic impacts of its technology and to assess the reduction of kerosene consumption.

Reduction of Greenhouse Gas Emissions

According to Lawrence Berkeley National Laboratories (LBNL) the primary source of greenhouse gas emissions in the developing world comes from dirty, hazardous and expensive fuel based sources for lighting. Fuel-based lighting in the developing world is a source of 244 Million tons of carbon dioxide emissions to the atmosphere each year, or 58% of the CO_2 emissions from residential electric lighting [17]. WLED lighting powered by renewable energy replaces fuel-based lighting thus reducing greenhouse gas emissions responsible for climate change. It is estimated that by replacing kerosene lamps with SSL technology approximately 130 kg of CO_2 emissions are reduced per household on annual basis[†]. By the end of 2005, LUTW intends to reach one million lives thus reducing over 26,000 tons of CO_2 emissions per year.

LBNL states explicitly that the only real way to meet the increasing lighting energy demands is to replace fuel based lighting with solid state lighting systems and recognizes LUTW as the pioneering organization in this effort.

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