PICO POWER – LIGHTING LIVES WITH LEDS

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Abstract
In the past 5 years, high brightness LEDs have begun to penetrate the lighting market. High brightness LEDs are attractive due to their high efficiency, very low power consumption and very long lifespans. This paper describes experiences in using white LEDs for lighting rural households in developing countries. The Light Up The World Foundation (LUTW) is an aid organization that has formed partnerships with a leading LED manufacturer to help deliver affordable benefits of efficient lighting services to those villages that do not yet have access to electricity. With new high power WLEDs, voltage regulation and current regulation are required for efficient use in solar home lighting systems. The lifetime of the devices is sensitive to temperature so the use of a proper heatsink is essential. Finally the LED enclosure needs to be appropriate to direct the light to where it is required. The long life of LEDs and low power requirements results in a village lighting system that has extremely low ongoing maintenance costs. LUTW estimates annual lighting costs of less than $10 per lamp per household for a white LED lighting system.

1 RURAL ELECTRIFICATION IN DEVELOPING COUNTRIES

Two billion people currently have no access to electricity [1]. However, energy is an integral part of these people's lives. Often, cooking fuel is in the form of biomass, and requires many hours per week to be collected. Crops need to be processed, such as rice dehusking and flour milling, and this is often done by hand. Village life is rarely relaxing, and tasks continue into the evening, using fuel-based light sources such as kerosene lamps, batteries, or resin-soaked sticks. Inefficient energy use in rural communities can result in deforestation, reliance on petroleum imports, health problems from smoke inhalation and hours each day of manual labour.

The provision of electricity can alleviate some of these burdens. In Nepal, locally manufactured micro hydro turbines are used to grind flour two to four times faster than by hand, which is usually the work of women and children. Women often prefer to walk to the next village to use a water-powered oil-expeller than to spend hours manually squeezing drops of oil from mustard seeds. The use of low-wattage rice cookers can preheat water using off-peak power, reducing the fuelwood consumption to sustainable levels and saving hours of collecting time. The hours saved can then be used for literacy programs or cottage industries, and electric lighting can help children study at night as well as providing a safer environment for household chores. A lamp outside the main door is also very good for keeping evil spirits away!

However, rural electrification is often a drain on government funds, requiring subsidies before electricity is affordable for rural households. Low cost design alternatives should be thoroughly investigated, and these designs must include an analysis of expected loads. In the poorer unelectrified regions, electric cooking and heating are rarely affordable for the majority of newly electrified households. Electricity is mostly desired for clean lighting, refrigeration, radio and television, as well as for small industrial uses during the day. Most rural electrification results in high peak evening loads and lower daytime loads. The majority of the evening peak load can usually be attributed to lighting, and therefore, efficient lighting alternatives need to be a key design feature for rural electrification in developing countries.

2 LIGHTING OPTIONS

Lighting alternatives for rural communities can either be electric or non-electric. Traditional electrical lighting alternatives include incandescent bulbs, halogen lamps, fluorescent lamps and other less used alternatives. Recent developments include high power factor compact fluorescent lamps, white high brightness LEDs and plasma lights. Non-electric options are mostly fuel-based – kerosene, batteries, resin-soaked kindling, etc. Non-electric lighting is grossly inefficient and very expensive. This is illustrated by using lumen-hours as a measure of lighting service. Most households that do not have access to electricity use some form of fuel-based lighting and spend around 2.5% of their income for this low quality service [2].

A wealth of literature exists discussing the lower life cycle costs of fluorescent lamps compared to incandescent bulbs, which needs no repetition here. Therefore, this study compares fuel-based lighting to fluorescent lighting and the latest white LEDs.

3 TECHNOLOGIES AND PROGRAMS

3.1 Fluorescent lighting

Fluorescent lighting, by far the most cost-effective method of household lighting, can be separated into two lamp types – linear tube fluorescents and compact fluorescent lamps, which have bent tubes. Linear lamps are available in sizes from 3W to 40W or larger. However, 20W and 40W lamps are the most common. Compact fluorescents (CFLs) are available from 5W to 30W, with a good range of intermediate wattages.

Linear fluorescent lamps have improved in efficiency in the past 15 years, resulting in smaller diameter tubes and increased efficiency, as well as a variety of warmer white colours. While T12 technology has been outdated in Australia for years, it still alive and well in many developing countries. Outstanding energy savings can be achieved by ensuring all manufacturers switch to more modern lighting technologies. Thailand's power generator EGAT managed this feat in 1993 [3], and expected a reduction in peak loads of 920 MW, due to a local market of 230 million fluorescent tubes accounting for 80% of all lighting. Most T12 lamps were phased out within 5 years, with marketing costs of around AU$10 million. That's about $11/kW!

Compact fluorescent lamps (CFLs) experienced teething problems in the 80's and early 90's. The lamps had heavy magnetic ballasts which had high harmonic distortion and low power factor, cast a bluish light and were rather large and awkward to fit when re-lamping. However, improvements in phosphors has allowed a significant reduction in tube size, and electronic ballasts now have power factors greater than 0.8 and low THD levels. There are also options in lamp colour, from a warm 2700K light like an incandescent bulb to a daylight-like 5000K. However, such issues are reserved more for the more fickle consumers in developed countries.

CFLs have been recognized in recent years as a cost-effective method of reducing greenhouse gas emissions. The Energy Saving Trust [4] in the UK is an example of a program that, after running multiple programs on various technologies, found that re-lamping with CFLs is one of their most effective programs. The Efficient Lighting Initiative [5] is another program that aims to promote efficient lighting in developing countries, and has a global outlook. ELI is an excellent source of high quality, low cost CFLs from manufacturers around the world. CFLs are also being used extensively as a demand side management option for evening peak load reduction (Ilumex in Mexico [6], Polish Efficient Lighting Project [7]) and delaying the building of large power plants (South Africa, Hungary).

China is the largest manufacturer of CFLs in the world, with an estimated production of 180 million per year in 1998 and growing quickly [8]. A few manufacturers have passed international quality testing procedures via the China Green Lights Program, and can now offer high quality lamps at lower prices than major manufacturers such as General Electric, Philips or Osram. The author used contacts from the ELI and CGL programs to procure lamps for AusAID village electrification projects in Nepal.

3.2 White LEDs

White light emitting diodes (WLEDs) were first available from a Japanese company, Nichia, around 1995 [9]. The basic concept is to coat an ultra-violet LED with a phosphor coat, thus producing white light. Previously white light could be obtained by mounting different coloured diodes closely on a circuit board and allowing the colours to mix to produce a white light. This can be achieved with just two colours (binary complementary colours), but this results in very poor colour rendering. Using three or more colours (RGB) gives satisfactory colour rendering. Using a mix of coloured LEDs is more energy efficient, as single colour high brightness LEDs are 3-5 times as efficient as current white LEDs. Some universities (eg. Boston University) and companies have made LED chips with multiple layers of different coloured LEDs, thus mixing the light within a chip and providing a more visually acceptable solution. The future will now be a battle between RGB LEDs and phosphor-based LEDs.

Phosphor-based LEDs have undergone rapid improvement in the last 5 years, with the two major companies emerging as Nichia and LumiLeds [10]. LumiLeds released a 120 lumen, 5 watt white LED in 2002, and Nichia have recently announced a 23 lumen white LED. The efficiencies of these latest WLEDs is 24 lumens/watt, which already surpasses incandescent bulbs (12 lumens/watt) and halogen lamps (15 lumens/watt). In contrast, fluorescent lamps and red LEDs have efficiencies of around 60 lumens/watt.

While manufacturers claim a lifespan of 100,000+ hours for LEDs, The Lighting Research Centre [11] found that early phosphor-based white LEDs underwent 40% light degradation in less than 4000 hours. However, such test results quickly become obsolete with each new development, and major lighting and semiconductor manufacturers are spending millions of research dollars on white LED technology. LumiLeds now presents light degradation data in their technical specifications, indicating manufacturers recognize the problem and are finding solutions. Both the US and Japanese governments are committing funds towards LED lighting research, with the aim of reaching 100 lumens/watt by 2010.

4 MARKET RESEARCH

Recent market research [12] indicates that the HBLED market is growing at 30% per annum and is a multi-billion dollar industry. There is approximately a 50% improvement in cost and efficiency of new HBLED technology every 18 months, which mimics the development of computing power in the past 30 years. This trend is set to continue with increasing participation by the private sector and support from Japanese and US research programs.

A recent study [13] estimates that fuel-based household lighting is a $32 billion/year industry, 30% larger than the market for electric household lighting. However, electrified households receive 300 times as much light as unelectrified households, as electric lighting was found to be 300-1500 times more cost-effective than kerosene lighting, in terms of $/lumen-hour of light. While the paper demonstrated vast potential for improving incandescent lighting by converting to CFLs, it also describes a far larger market of households that still rely on the most expensive and inefficient sources of light.

5 LIGHT UP THE WORLD – WLEDS FOR RURAL ELECTRIFICATION

The Light Up The World Foundation [14] (LUTW) is a non-profit organization founded by Professor David Irvine-Halliday, which, for the past 5 years, has been financing, designing and installing white LED household lighting systems in developing countries. Dr Irvine-Halliday was struck by the poor living conditions of villagers during a visit to Nepal in 1997, and using his background in photonics, investigated the option of using white LEDs for lighting village households. To date, LUTW has brought light to more than 700 households, 3 schools and 4 temples in 7 different countries around the world, and have associate organizations in many more countries.

WLEDs are not yet cost competitive with CFLs, but they offer one major advantage over all other light sources – longevity. If WLEDs last their rated 100,000 hours, and villages use their lamps for 12 hours each day, the lamps should last for 23 years. LUTW's oldest village lighting system is now 2 years old, and is running successfully through –15°C winters and a civil war at 2400m in the Himalayan foothills of western Nepal. Many other projects have been installed, and a common feature has been the high level of interest from surrounding villages. Demand far exceeds LUTW's funding.

6 LOW-LUMEN LIGHTING DESIGNS

LUTW-designed WLED lamps require only 1 W, and households therefore require less than 5 W for functional lighting levels. This household demand is far reduced from 30W for CFLs or 100W for incandescent bulbs, although obviously for a lower lighting level. Of the typical 1500 lumens of light generated by 100W of incandescent lighting, much of it is wasted. Losses result from lack of luminaries, dark walls and ceilings and lack of direction. Often, the most basic step of using a luminaire (light shade) is not considered, even though this would double lighting levels in activity areas.

There is considerable scope for designing a low-lumen lighting system for village households that is minimal yet functional. For example, people rarely read near the ceiling, so lighting levels above lamps should be minimal. The majority of activity in a Nepali household takes place in one room near the stove, so simply providing lighting levels above 25 lux in this area is sufficient for most tasks, while walls may need only 5 lux. Such a lighting design may only require 10% of the energy of the "bare-bulb" lighting systems which dominate most rural households in developing countries.

7 EXAMPLE SYSTEMS FOR VILLAGES

One of LUTW's first projects demonstrated the social acceptability of low-lumen lighting solutions. A 200W pico hydro was powering incandescent lamps in 2 households of Thalpi, in western Nepal [15]. LUTW offered to connect all 30 households using 1W WLED lamps if sufficient power was available. A village meeting was held, and the two households agreed to relamp so that the other households could access the power. The villagers were deeply involved during construction, and were found to be satisfied with the lighting levels. The directional lighting produced a beam as strong as a 40W bulb, and many men used the light for reading. Female literacy is approximately 10%, so women used the light for mostly food preparation. Often, lamps were left on all night to keep evil spirits at bay.

The Lamra village project in western Nepal uses a 200W pico hydro turbine to generate power for 55 lamps in 53 households. The project cost $7000 to install, giving a cost of $132 per household. In comparison, a nearby AUSAID-funded microhydro project for 70 households used a design of 100W of incandescent lighting per household, resulting in an 8 kW system being installed. This project cost $50,000 to construct or $714 per household – 5.5 times the cost of the WLED system. Interestingly, these 70 households are surrounded by 500 additional households with no electricity. By relamping with a combination of two WLED lamps and one CFL per household, consuming 10W, all households could be connected for $75,000, or $150/household. All households use the water-powered grinding facilities during the day, so extending lighting services would be a natural extension. Income would increase by 700%, greatly improving the financial viability of the AusAID project.

Pico hydro has exciting potential throughout the Himalayas. It is estimated that there are 200,000 traditional water mills serving millions of rural inhabitants of India, Nepal and Bhutan. These can be upgraded for around $800/kW to produce up to 3 kW, which, when coupled with efficient lighting, can serve large villages during the evening, as well as run agro-processing machinery during the day to reduce women's manual labour.

Several more recent projects use standard 30Wp solar home systems to function as a centralized charging station for households with 7 Ah motor batteries, or link up to 8 households together to one system, thus forming DC mini-grids. Recent field experience indicates that both voltage and current regulation of WLED lamps are required. Different batches of WLEDs from the same manufacturer have different characteristics, so driver circuits need to allow for this, while optimizing the light output. Heatsinks are also required, as the life of the LEDs is dependent on operating temperature.

8 ECONOMIC ANALYSIS OF VILLAGE LIGHTING SYSTEMS

By sharing solar home systems between households, the $750 capital cost can be spread between many households. Table 1 indicates how this translates into lower annual costs for repaying a system. There are several examples of rural energy service companies in developing countries that use similar long-term financing structures to reduce the barrier of high capital costs for renewable energy-based electrification systems.

The longevity of LEDs translates to extremely low maintenance costs for villages. There is considerable scope to extend financing for the LED lamps to as much as 15 years, reducing repayments even further. Pico hydro systems reduce costs through low cost manufacture of turbines and eliminating the need for energy storage with batteries. The $7000 Lamra system financed over 25 years at 5% interest would only cost villagers $10/year/household, including $75/year for maintenance. Therefore, white LED based lighting systems can offer a markedly lower entry point for rural lighting services.

Several parameters can be used to estimate efficiency of lighting service delivered. Mills [13] has used $/lumen-hour, as this captures capital costs and ongoing fuel costs, as well as the longevity of the lighting source. Table 2 compares several lighting sources, including both lamp purchase and their associated energy costs. The Lamra pico 200W pico-hydro project was estimated to last 15 years, and has a higher energy cost than large micro hydro projects or grid electricity, which has been assumed as the fuel source for bulbs and CFLs. The table demonstrates that LED lamps are already far more efficient than kerosene wick lamps in delivering lighting services. It also demonstrates that cost per lumen is a poor means of measuring lighting services, as is cost per lumen-hour if energy consumption costs are not added to the lamp cost.

Figure 1 attempts to forecast the next 10 years of white LED development, with the following assumptions:

- an annual 15% decrease in lamp costs,
- a 5 lm/watt/year increase in WLED efficiency from a base of 17 lm/watt in 2000,
- a 5%/year decrease in $/kWh as pico power generation costs decrease through higher production volumes
- a 3%/year increase in grid electricity $/kWh.

9 EMISSION REDUCTIONS

Field survey results from Nepal [16] and discussions with experts [13] lead to an estimated average kerosene consumption of 3.5 L/month/household, or 42 litres per household per year for home lighting. This is consistent with recent field data collected by LUTW in Nepal, Sri

Lanka and India. Based on Mills' emission conversion of approximately 400 litres of kerosene per tonne of CO_2 released, it would take an average rural household 9 years to release one tonne of CO_2. Considering RECs are worth approximately \$30/tonne of CO_2, emission credits of approximately \$3/household/year may be earned through village lighting projects. Compared to annual repayments of \$10-54, depending on the system installed and financing parameters, emission credits may or may not be a significant source of income.

The Dutch government has recently started accepting submissions from developing countries for emission reduction projects through their CERUPT project. It is expected that similar programs will materialize in coming years so earning income from carbon credits is an emerging reality.

10 RELAMPING AUSTRALIA AND LIGHTING UP VILLAGES

A study by the Lighting Research Centre [17] found each traffic signal uses about 1 MWh/year, and that there are 3-4.5 million traffic signals in the USA. Therefore, the estimated energy used by traffic signals was estimated at 3 million MWh/year, and could be reduced by up to 90% by using LED technology.

With 5% of the population of the USA, it is roughly estimated that Australia has about 150,000 traffic signals and could save 150 GWh/year by relamping them. Assuming the value of the emission reductions is \$30/MWh, as measured by Renewable Energy Certificates, relamping could generate \$4.5 million per year in RECs, which would bring electricity to 100,000 villagers a year. It is this combination of new technologies and incentives for the efficient use of energy that can create win-win scenarios for developing and developed countries.

Similarly, CFL "power plants" would help reduce peak loads in Australian cities as well as reducing greenhouse emissions. There are approximately 6 million households in Australia. The installation of just one CFL per house would, assuming an annual energy saving of 100 kWh/lamp/year, result in 300 MW peak load reduction and 600 GWh/year of energy savings. Therefore, by promoting energy efficient lighting in Australia and capturing the RECs value, LUTW could bring electricity to half a million villagers every year. Even 1% of this would be a good start, but first CFL relamping projects must be able to generate RECs. Considering solar hot water heaters can generate RECs by reducing household energy consumption, it stands to reason that efficient lighting should be allowed the same incentive.

11 CONCLUSION

White LEDs are an exciting new technology that have been shown to be a cost-effective alternative to kerosene-based lighting in developing countries. By forming strong relationships with manufacturers, a non-profit organization called Light Up The World hopes to help deliver this technology to where it is most needed – rural villages in developing countries. However, affordability will only come with extended terms of credit. Alternative metrics for measuring the efficacy of lighting for the poor should be more rigorously assessed.

By forming strong relationships with manufacturers, Light Up The World is delivering pico power solid state lighting where it is most needed – rural villages in developing countries. By building on an international base of projects, LUTW actively plans to facilitate a trickle-up market penetration of white LED home lighting sytems, creating jobs and local support structures along the way to ensure clean, efficient lighting services.

Table 1 – Comparing a conventional SHS with a shared SHS using WLED lamps

Financing options (in	Interest	Cap. Cost	Years	Annual
Battery and	10%	\$ 235	5	\$ 62
Balance of 30W solar	10%	\$ 515	8	\$ 97
Annual cost for 1 household, 30 W solar home				\$ 159
Extra wiring and LED	10%	\$ 1,449	8	\$ 272
Total for connection of 8				\$ 430
Divide annual cost between 8				\$ 54

Table 2 – Performance comparison of lighting sources

	25W bulb	*7W CFL*	*1W WLED*	*Kerosene wick*
Lamp cost	$1	$10	$25	$1
Lumens	250	250	17	10
Lamp life (hours)	1,000	6,000	100,000	5,000
Practical life	1,000	6,000	50,000	5,000
Lumen-hours per $	250,000	150,000	34,000	50,000
Fuel cost*	$0.15	$0.15	$0.65	$1.00
Lamp consumption**	25	7	1	0.05
Lifetime energy***	25	42	100	250
Energy cost	$3.75	$6.30	$65.00	$250.00
Total cost	$4.75	$16.30	$90.00	$251.00
Lumen-hours per $	**52,632**	**92,025**	**18,889**	**199**
Total cost per lumen	$0.02	$0.07	$5.29	$25.10

*$/kWh for electric lamps, $/L for kerosene **Watts for electric lamps, L/hour for wick lamp
***kWh for electric lamps, litres for kerosene

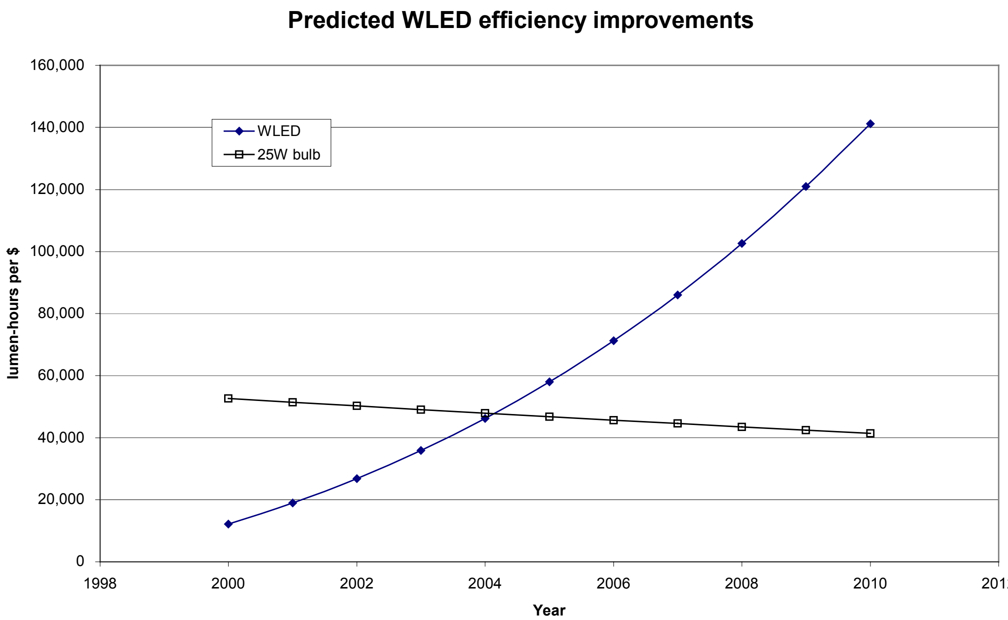

Figure 1 – Predicted WLED efficiency improvements

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