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LEDs IN DEVELOPING WORLD

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Every fifth inhabitant of our planet has no access to electric lighting. Most of them are poor people living in remote areas of developing countries. Recent progress in solid-state lighting technologies offers good opportunities to develop, commercialize and introduce off-grid lighting systems based on application of white light emitting diodes (WLEDs) in combination with photovoltaic solar panels, wind generators or tiny hydro power plants. Though strongly dependent on the mainstream progress in implementation of LEDs for general lighting, application of this technology in developing world has specific challengers, difficulties and even advantages. Lighting technology the developing world is up to leapfrog from splinters and kerosene wick lamps directly to LED lamps leaving incandescent and fluorescence lamps behind. Achievements and problems, history and future of implementation of solid-state lighting in remote villages of developing counties are discussed in this chapter.

Keywords: light-emitting diodes; lighting; renewable energy; rural electrification.

1. Introduction

When asked about the major problems related to energy supply and consumption, most of the citizens of developed countries would probably mention a drastic reduction in fossil fuel reserves, pollution due to increasing exploitation of the fossil fuel, and increasing dependence of countries poor in energy resources on energy-rich countries. You can hardly expect many people in US, Europe or Japan pointing out to the strikingly inhomogeneous distribution of energy consumption among the 6.8 billion inhabitants of our planet. Meanwhile, the International Energy Agency estimates that 32% of the population in the developing non-OECD countries (excluding non-OECD Europe and Eurasia), i.e. about 1.6 billion people, did not have access to electricity in 2005 [1]. The worst situation is in sub-Saharan Africa, where more than 75% of the population still remains without access to electric power. It is worth noting, however, that the rate of the net electricity generation in the non-OECD countries increased at the verge of the new millennium and has now a stabile average value of 3.5% per year (4.4% in China and India). This rate is forecasted to remain stable up to 2030. This forecast is supported by a high projected economic growth rates in non-OECD countries. In contrast, net generation among the OECD nations grows and is forecasted to grow by an average of 1.2% per year from 2006 to 2030. Approximately in 2011-2012, the net electricity generation in non-OECD countries, where a large amount of demand goes unmet at present, will surpass that in the OECD countries, where electricity markets are well established and consuming patterns are mature[2]. Thus, two peculiarities might be emphasized from the point of view of possible LED applications: i) products and services related to electricity generation and consumption in non-OECD countries have large and rapidly growing markets, ii) most of those 1.6 billion people without access to electricity live in remote areas, where electricity supply lines are definitely not expected in the foreseeable future.

LED-based lamps have extraordinary advantages for applications in remote areas. Since most of such areas are in developing countries, the LED-based lighting there gets additional dimensions (logistic, social, cultural, even religious), has strong financial problems and encounters specific technical challengers.

Recent developments in exploitation of renewable energy sources resulted in design of small autonomous facilities quite efficiently converting the energy of the Sun, wind and running water directly into electric energy. Combination of such facilities with white LEDs (WLEDs) offers a unique chance for fabrication of lighting systems suitable for using in remote areas. Such systems could drastically improve the life of many poor people in many poor countries. Moreover, the LED-based lighting in developing countries might turn out to be not only technologically feasible, but also economically viable to take a considerable share of those $38 billions, which are spent annually worldwide for fuel used for lighting [3]. A substantial contribution in spreading the LED-based lighting technology to remote areas might be expected from countries currently exhibiting fast economical and technological development, especially from China. Furthermore, implementation of the LED-based lighting in developing countries might also have a considerable contribution to reduction of the greenhouse gas emission. The world-wide carbon dioxide emission due to combustion of fuel for lighting (190 million metric tones per year) is equivalent to one-third the total emissions from the U. K [3]. Prospects and problems of implementation of the LED-based off-grid lighting is the topic of this chapter.

2. Need for light worldwide

It is usually assumed that introduction of LED-based general lighting can decrease consumption of electricity for lighting by 50%. In 2007, 19,8 TWh of electricity was produced worldwide[4]. Approximately 20% of this electricity was used for lighting. Consumption of electricity for lighting in Europe is ~15%, however, the percentage in countries with underdeveloped industry reach up to 95%. Consequently, saving energy by introducing the LED-based lighting is much more substantial in developing countries than that in developed ones. Side by side with the direct benefits for the developing countries, the energy savings would result globally in decreased CO_2 pollution due to burning fossil fuel. Electricity consumption in many developing countries increases and will increase at a high rate. The growing demand for electricity in these countries is and will be met by exploiting the least expensive energy sources available. In most cases, the increase in electricity production will be achieved by burning fossil fuel. In view of the increasing awareness of global warming and ongoing political debates about measures for cutting CO_2 emissions, financial aid of the leading industrial states for introduction of solid-state lighting in developing countries might turn out to be very competitive by efficiency in comparison with the other possible forms of the international sponsoring of measures for greenhouse gas emission reduction in poor countries. From the technical point of view, the problems of solid-state lighting for consumers connected to the power grids are basically the same anywhere around the globe. Penetration of the LED-based lighting in the nearest future will obviously depend on a tradeoff between color rendering and price. Low-price LED lamps (at certain expense of color rendering) might become acceptable first of all for consumers in developing countries, where electricity is more expensive (especially in comparison with the income level there) and gain in exploitation costs by using LED lamps is considerable higher. On the other hand, the high initial capital costs of an LED lamp are more problematic in developing countries.

Combination of autonomous electric power generators using solar, wind or hydroenergy with LED lamps opens previously unavailable chances to get access to electric lighting for many dwellers of remote settlements and villages with no connection or even no reasonable hope for connection to national or regional power grids. In most sub-Saharan African countries like Kenya the overwhelming majority of the population lives in the rural areas, where the penetration of grid electrification is of the order of 1% [5]. Low population density or/and difficult terrain (e.g. mountains, dense forests) make grid electrification of many remote areas economically impossible even in foreseeable future. High efficiency, good directionality, low voltages and low currents needed, ruggedness and long lifetime of LED lamps offers chances for households in those remote areas to get electric lighting by leapfrogging such century-old conventional light sources as incandescent and fluorescence lamps.

3. The beginning of the idea. Light Up The World

In 1997, while on sabbatical at Tribhuvan University in Kathmandu, Nepal, Dr. Dave Irvine-Halliday, a Professor of Electrical Engineering at the University of Calgary realized a great need for simple, safe and healthy, rugged, and affordable electric lighting for remote villages in developing countries. Favorable conditions in Nepal for exploitation of solar, wind and hydropower and emerging technology of high-brightness white LEDs encouraged design of autonomous lighting systems suitable for remote rural areas [6]. The first prototype WLED lamps were tested in Nepalese villages by Dr. Dave Irvine-Halliday and his wife, Jenny, in 1999. In 2000, four Nepalese villages become the first worldwide to get WLED-based lighting. These activities evolved into a global lighting initiative. The Light Up The World (LUTW) was established as a legal entity in 2002. Since then, LUTW has grown to a highly professional, globally active humanitarian organization with important links in industry, academia and civil society world-wide, both in developed and developing countries. In 2007, Light Up The World Foundation merged with the EnerGreen Foundation to become Light Up The World (LUTW, www.lutw.org).

Three energy sources (pedal generators, pico hydro generators and solar cells) have been used in the pioneering six village lighting pilot projects implemented by LUTW in 2000. Their characteristics are summarized in Table 1.

Table 1. Description of LUTW pilot projects installed in 2000. Aftter [6].

Location	Thulo	Raje Dunda	Jumla	Bhaktapur	Norung
Power source	pedal generator	pedal generator	pico hydro (200 W)	220 AC, grid	centralized solar charging station
# of homes	23 + Gompa + school	31	28	12 lamps	45
LEDs/lamp	6 (homes) 9 (others)	6	9 and 6	3,6 and 9	9
NGOs involved	LUTW, Nepal Schools Project	LUTW, Nepal Schools Project	LUTW, KCST, A. Zahnd, S. Craine	LUTW, Child Haven Intl(Canada)	LUTW, A&F Harckham(Canada)

By 2009, LUTW has brought light to more than 17,000 homes in 51 different countries. Over 2,000,000 people have been impacted directly by LUTW activities. LUTW activities are targeted on extensive seeding of the LED-based lighting worldwide and fostering further development of this new lighting technology by NGOs (Non-governmental Organizations) and local companies.

To accelerate and replicate the adoption of solid state lighting, LUTW actively seeks strategic alliances with i) delivery partners (affiliated NGOs and other organizations trained by LUTW), which have the capacity and field networks to implement the LED-based lighting in developing countries, ii) industrial supply chain partners (manufacturers of WLEDs, solar panels, and batteries), iii) local enterprise partners in the countries of LUTW activities to ensure maintenance, support services and new installations after the initial LUTW projects have seeded the solid-state lighting technology, iv) international and local financial agencies to raise funds for new projects and to assist the poor in getting micro and merchant credits and establishing co-operative initiatives.

4. Predecessors of LEDs

Open fire is used for lighting since the very dawn of our civilization up to now. Bonfire, fireplace for cooking and room heating, torches usually made of rope impregnated with tallow, pitch, or resin, splints made of resinous wood, wick lamps, primitive candles[7] are obsolete but still in use as light sources, in spite of being very inefficient and harmful for health.

In high-altitude Nepalese Himalayan villages, the only sources for indoor lighting are open fire used for heating and cooking and resin-soaked pine sticks *jharro*, used specifically for lighting. To produce the *jharro*, a notch in pine tree bark and top layer wood is made. Additional amount of pine resin accumulates around the “wound”. After a week or so, the resin-soaked wood is split out of the tree trunk. After the first harvest of the resin-soaked wood, the wound in made deeper and new sticks are split off step by step afterwards until the tree dies (see Fig. 1).

The wood sticks prepared using this technique burn like a small torch. To light a room, one end of the *jharro* is usually fixed on elevated stone or mud pile at a height of 40-50 cm from floor, and light is set to the other end of it (see Fig. 2). The average illuminance on the floor at a horizontal distance of 1 m from the burning *jharro* is typically 2 lx [[8]]. In the rest of the room, the illuminance decreases well below 1 lx and is sufficient only for moving around the room. Doing some general work is possible only close to this light source, but the *jharro* lighting is not adequate for any visually oriented tasks such as reading. It is important that the burning resin-soaked wood emits smoke containing a lot of CO, CO_2, and particulates, both PM_{10} , thoracic fraction with particle size of <10 μm, and $PM_{2.5}$, respirable fraction, <2.5 μm [[9]], which are hazardous for health of the people living in the room, especially for women who spend more time indoor than men do.

Fig. 1. Pines exploited for *jharro* production [9].

Highly resinous wood of Himalayan pine (*Pinus Wallichiana*) growing in mountain valleys at high altitudes of 1800-4300 m is especially good for making *jharro*. The use of pine wood for *jharro* production has, however, a devastating impact on Himalayan forests. It contributes to severe deforestation of Himalayan mountains, which is mainly caused by use of precious trees for firewood inefficiently burned on open fireplaces indoor for cooking, heating and, in parallel, for lighting. A household in Nepalese mountain villages consumes 20-40 kg of firewood a day [[10]].

Fig. 2. Room with open fire for cooking and *jharro* for lighting in remote Nepali village. [Courtesy of Alex Zahnd]

Consumption of *jharro* wood has been measured at Helsinki University of Technology [8]. One *jharro* lamp emitting 88 lumens consumes 0.27 kg of resin-soaked wood per hour. Thus, the daily consumption of *jharro* lighting for 3 hours a day requires approximately 0.8 kg of the resin-soaked wood prepared as described above.

Kerosene (kerosine) is a mixture of hydrocarbons having 11 or 12 carbon atoms and boiling at temperatures of 160-250^{0}C. Crude oil is the main source of kerosene. One of the names of crude oil *naphta* has its origins in a Persian word meaning a pit (petroleum seep pit). In ancient world, crude oil was used mainly for impregnation of boats, folk medicine, but hardly for lighting. Lamp oil refined from crude oil was introduced in Abaside Caliphate around the year 850. This lamp oil (kerosene) was produced using an apparatus similar to the pot still, which is used for distilling whisky and brandy nowadays. Nevertheless, kerosene did not become a dominant lighting liquid in "developed" countries until the XIX century. For centuries, whale oil was used as a convenient combustible liquid in wick lamps for both indoor and outdoor lighting. However, an increasing number of unlighted streets of rapidly expanding European and American cities and towns in the second half of the XIX century evidenced increasing crime, while the number of whales drastically decreased. Numerous scientists and inventors in different counties contributed to development of a new lighting liquid. The name kerosene (a contraction of *keroselaion*, meaning *wax-oil* [[11]]) was coined by Canadian geologist A. Gesner, who demonstrated a new kerosene production process discovered by him in 1846. In the UK, South East Asia and South Africa, kerosene is called paraffin or sometimes paraffin oil. Kerosene has been extracted from coal, oil shell, however, crude oil proved to be the most suitable stock for kerosene. Kerosene production boosted after the first oil wells were drilled in Romania in 1957 and, most importantly, close to Oil Creek in Pennsylvania, USA, in 1959. Those days, only up to 15% of crude oil was extracted as kerosene. Approximately 10% of the crude oil used to be processed to considerably less useful liquid called gasoline (gas) in US and petroleum (petrol) in Great Britain. The rest ~60% were considered as waste and abandoned. Fast development of automotive industry demanded an increasing amount of gas (or petrol), while introduction of cracking process (transforming heavy hydrocarbons into simpler molecules by breaking of carbon-carbon bonds in the precursors) on industrial scale enabled doubling the yield of the light fractions of crude oil. Today kerosene is a major component (~60%) of jet fuel in aviation.

A considerable share of kerosene is still used for lighting. For example, 600 million people in India live without electricity. Even in electrified villages, about 65% of households do not receive benefits of electricity, since only higher-income families can afford electric lighting [[12]]. Furthermore, many electrified households use electric lighting only in living rooms and outer verandahs, while kerosene-based lighting devices are being continuously used in the kitchen and for other miscellaneous activities. According to a survey of 1999 in the rural areas of Uttar Pradesh, India, the electrified households there used kerosene lamps for more than 4 hours on average. 85% of the households were using homemade wick lamps, while the rest possessed hurricane lanterns [[13]]. Luminous efficiency of the wick lamps is very low. The total annual light output of a simple wick lamp (approximately 12,000 lumen-hours) is equivalent to the output of a 100-watt incandescent bulb in 10 hours [3]. Most of the wick lamps are homemade using a glass bottle as a kerosene container and a scrap of cloth as a wick. Hurricane lanterns, kerosene petromax, and non-pressure mantle lamps have a higher luminous efficiency. Anyway, kerosene for lighting is an expensive item on the budget of many poor families. Kerosene and liquid propane gas subsidies for these people in India for the year 1999 were of the same magnitude as subsidies for education [[14]].

A villager using 1 liter of kerosene per week at a typical for remote areas price of $0.5 – $1 per liter pays $30-50 a year, and this is a considerable budget share of many families. It is worth noting that the capital costs of a lighting system based on photovoltaic cell (PVC) and LED is approximately $100, and the system serves supposedly for ~20 years with one or two battery substitutions as practically the only item of maintenance costs.

Incandescent lamps with only ~5% of electric energy emitted in visible (luminous efficacy of 15 lm/W) dominated the market of lighting sources for a century. However, good color rendering and small capital costs of a bulb (though working for 800 hours or even less) did not help this common light source to resist the decisions of politicians seeking popularity on environmental issues. Ban for selling incandescent lamps is planned and is being implemented in many industrial countries, though with different timing. The current pushing the incandescent bulbs out from the markets in industrialized countries might temporary increase their supply to the lighting markets in developing countries at more attractive pricing then before. However, the technology of incandescent lamp production has been developed so high that a considerably discount in their price can hardly be expected. Thus, the incandescent lamps, which traditionally have market in developing countries due to their low purchase price, do not seem to have a promising future.

Fluorescence lamps and, especially, compact fluorescence lamps (CFLs), currently are coming into market worldwide as a more efficient alternative for incandescent bulb. It is worth noting, however, that certain advantages (higher efficiency, longer lifetime) and disadvantages (higher capital costs, poorer color rendering) of CFLs are identical with those of LED-based lamps. Thus, these two lighting technologies compete mainly on the same grounds. Efficiency of CFLs is limited at approximately 90 lm/W due to physical restrictions, which can not be excluded by any further development of CFL production technology. Meanwhile, efficiency of WLEDs already passed this 90 lm/W value and has a good prospective for increasing further. Thus, in case of a successful progress of LEDs in the capital costs and lumen-per-watt costs in the nearest future, the LED-based lamps had a chance to actually leapfrog the CFLs in the developing countries, where the penetration of CFLs is still not high, even in the on-grid areas. The low lumen-per-watt price, long lifetime, ruggedness and low voltages and currents needed are additional advantages of LEDs over CFLs for electrification in off-grid remote areas.

The costs of lighting provided using different light sources in usual equipment configurations are compared in Fig. 2. In the figure, the costs of purchasing the lighting source corresponds the Y axis intercept, while operating costs (electricity, fuel, replacement batteries, lamps, candles, wicks, etc.) are reflected by the slopes of the lines corresponding to different lighting sources.

According to Fig. 3, in comparison with hurricane kerosene lamp, the payback time of the system consisting of solar panel and WLED is approximately 10 months. Currently, the payback time decreases with increasing efficiency of WLEDs. Thus WLED-based lighting is a technology economically competing all the other lamps available. High initial price is, however, still a disadvantage. On the other hand, traditions in using obsolete lighting sources and unavailability of WLED-based lighting systems in remote areas are also hindering penetration of the new lighting technology into rural areas of developing countries.

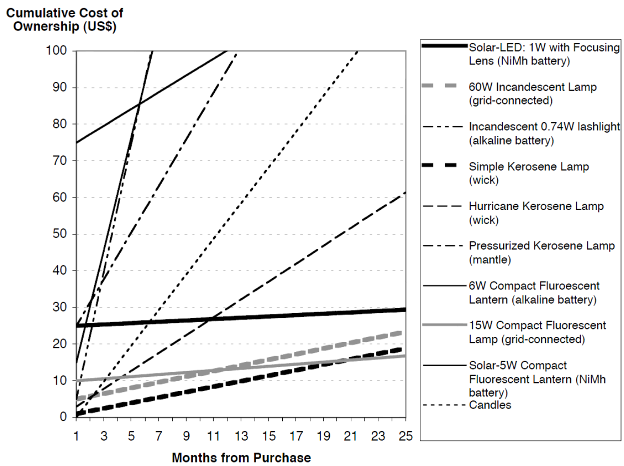

Fig. 3. First costs (y-intercept) and cumulative operating costs (slope) of different light sources [3].

5. Rural lighting requirements

Most of the LED features, which are usually pointed out as advantages over the conventional light sources, are of especial importance when the LEDs are exploited in autonomous systems for lighting in remote areas:

i) In principle, LED is an ultimate light source, since LED efficiency might be increased up to 100% without physical limitations. The reasonable limit due to technological problems is considerably lower, but most of the leading WLED producers exceeded the luminous efficiency of 100 lm/W already in 2007. The luminous efficiency of the most important WLED competitor, a compact fluorescence lamp depends on its power and construction, but anyway is lower than 100 lm/W due to physical limitations. Thus, WLEDs are already quite efficient light source with good prospects for further increase in efficiency. The higher efficiency enables a decrease of the capital costs per household of the lighting systems in remote villages, since more households can be electrified using the same capacities of battery banks and power of PVCs or wind generators. Naturally, a tradeoff between efficiency and price is of crucial importance, since the cost of WLEDs comprises a large share of the total lighting system. The trends [15] of increase in luminous flux of a typical LED chip by a factor of ~20 per decade at the decrease in the price of the corresponding typical LED by a factor of ~10 are encouraging for the future. Nowadays, the further WLED progress is strongly inhibited by efficiency droop phenomenon, i.e. by a decrease in LED efficiency when the driving current is increased to obtain a higher luminous flux. Note, however, that WLEDs with lower luminous flux (and, correspondingly, with higher efficiency) can be exploited more conveniently in the lighting systems for remote rural areas than for those designed as a substitute for the conventional lighting in developed countries. The recently exploited approach of avoiding the efficiency droop by increasing the LED chip area is also acceptable for the remote systems without much problems.

ii) The LEDs have a long lifetime, usually declared as 100,000 hours. This is an especially important advantage for use in the lighting systems anticipated to operate for a long period of time without any qualified maintenance services. The anticipated lifetime of the PVC-based lighting systems for remote areas, which are being installed nowadays, is limited by PVC lifetime, supposedly, 25 years.

iii) Low voltages (1.5-3 V) and low currents (tens of mA) ensure safety of simple and inexpensive installation wiring inside narrow rooms in primitive houses and for transmission lines within the village lighting system. This LED feature ensures an especial compatibility in PVC-based lighting systems.

iv) In comparison with all other light sources, small and rugged LEDs have an advantage of mechanical resistance.

Some disadvantages of LEDs in comparison with other light sources are considerably less important in the lighting systems designed to replace wick oil lamps than in general lighting systems, where LEDs substitute incandescent and fluorescence lamps. To ensure significant penetration into the market of general lighting, the color rendering of the currently most developed and cost-efficient phosphor conversion WLED consisting of InGaN-based chip and a single YAG:Ce phosphor has to be improved. Meanwhile, the color rendering of these WLEDs is quite sufficient for electrification of remote villages. The optimal power of the lamps to be used in remote villages is quite low, thus the problems of heat dissipation are not as important as in the high-power LED-based luminaries designed to replace conventional lamps.

Some time back, government institutions and rural electrification agencies in developing countries usually assumed that each household needs access to a minimum power rating of 100 W (2 or 3 incandescent bulbs per household, each consuming 25-60 W). Such a power rating is obviously too high for remote areas with limited power generation capacities by PVCs, simple wind turbines or picohydrogenerators [16]. The optimal illuminance to be targeted in a living room of a remote village house has to be selected as a tradeoff between need for better visual environment and affordability. Human eyes can adapt to illuminance within a wide range between approximately 10^{-4} lx (typical of starlight at night) and 10^{8} lx (blinding illuminance). Room illuminance in developed countries is usually maintained at 30-100 lx for orientation and simple visual tasks in public spaces and at 300-1000 lx for common visual tasks. Even an economical lighting system has to ensure performance of simple visual tasks (cooking, child care) and provide a comfortable and pleasant visual environment. The choice of illuminance is limited mainly by the capital costs of the lighting system. The availability of the local energy resources and the prevailing lighting practices of local people have also to be taken into account.

Primarily LUTW targeted at the lighting level of 50 lx in reading areas, 25 lx in major working areas used for cooking, food preparation etc., and 5 lx areas of occasional use [6]. Later on, the issue of optimal illuminance has been studied in more detail in rural Nepali homes previously lit by *jharro* [8]. The average illuminance available on the floor was approximately 2 lx. This illuminance level was found to be insufficient. Illuminance of 5-15 lx was suggested as a target for introduction of LED lighting. Minimal illumination for reading tasks is ~25 lx. Thus, reading tasks have to be performed in close proximity to the light source.

Fig. 4. Two types of LED luminaires manufactured by Pico Power Nepal, a local Nepali company [8].

Two types of LED luminaires manufactured by Pico Power Nepal, a local Nepali company, have been used in the village illumination programs implemented by NGO RIDS-Nepal for few last years (see Fig. 4). The first luminaire consists of nine low-power Nichia white LEDs (NSPW510BS), consumes 0.73 W of electrical power, emits luminous flux of 11 lm and has luminous efficiency of 15 lm/W. A single high-power white LED, Luxeon Star from Lumileds, is used in the second luminaire (1.07 W, 14 lm, and 13.1 lm/W, respectively). The luminaire with low power LEDs is driven by using series resistors and a reverse protection diode. Three strings, each string containing three LEDs, are connected in parallel and with one resistor. Due to small LED driving current (20 mA), the losses in the resistors are insignificant. Meanwhile, the driving current of high power LED used in luminaires of the second type is 350 mA. Thus, these luminaires were equipped with a switching regulator to avoid high power losses, if driven simple with a resistor. Inexpensive aluminum cups are used as reflectors in these luminaires.

Each home, typically consisting of two rooms, was provided with three luminaires: two low power LED luminaires were installed in the bigger room used for cooking and the luminaire with a single high-power LED was installed in the smaller room. The luminaires were installed on the ceiling of the room at a height of ~1.8 m from the floor.

The average illuminance at the floor level in the bigger room with the two luminaries was 5 lx. One luminaire with the high-power LED in the smaller room ensured lower average illuminance on the floor (3 lx). Interviews showed that the average illuminance of ~5 lx is anticipated by local people as adequate for general purposes, while illuminance of 3 lx was too low. Illuminance 0.5 m below the luminaire with low-power LEDs was ~110 lx and was sufficient for reading.

Fig. 5. Two types of LED luminaires manufactured by Pico Power Nepal (PPN), a local Nepali company [8].

6. Lighting systems for remote areas

Since the energy consumption of the LED-based lighting is quite low, pedal generators might be considered as a viable option for electricity generation. Such generator systems have been tested in remote Nepalese villages since 2001 [6]. The battery charging system consists of a low rpm DC motor/generator, a speed-increasing pulley, poly-fiber belts, a voltage regulator, and a digital multi-meter. Approximately 30 minutes of slow pedaling is sufficient to charge a battery to light a room for one evening. Several batteries can be charged in parallel, one generator system can be shared between up to 8 households. Later on, inspection of the systems in use showed that batteries are often charged irregularly. As a result, deep discharges occur and deteriorate the battery. To prevent premature failure of the batteries, they were equipped with a low-voltage disconnecting switch.

Small hydro power plants can be effectively used for village electrification in remote areas. Using LED-based lamps reduces the total power needed for lighting down to 100-300 W for a small village. A term pico hydro power plant is coined to point out the extremely small power of these installations. Dams previously used for water mills can be used for installation of the electric power generators. These pico power plants serve as a niche markets for production of small companies in the developing countries. Many universities in these countries select electric power generation at small hydro power plants as priority direction for research and teaching.

Efforts of both international companies and local business and academia expand exploitation of wind generators for electricity supply in remote areas. These generators find an easier way for broader penetration in regions, where wind mills were traditionally used for water pumping and other purposes.

Solar panels are very attractive sources of electricity, especially in desert and mountain areas with low nebulosity. Very favorable conditions for solar electricity generation are in countries within the "solar belt" between latitudes of approximately 40^0N and 40^0S, which, in turn, is created by atmospheric circulation due to solar heating. The heated air rising from the equator area moves polewards near the tropopause, sinks at the latitudes of 30^0 and returns equatorward near the surface. This atmospheric circulation pattern, which is called Hadley cell, causes the air pressure at the latitudes of 30^0 to increase and creates favorable conditions for solar radiation to reach the Earth surface. At the latitudes of 25^0N, the yearly daylight is about 4500 h, and 70% of this is the sunshine time. Hourly power densities of solar radiation 1 kW/m^2 and more are measured.

High-quality silicon PV panels have warranty for 25 years. Current experience proves that the lifetime of 25 years can be expected even for the PV panels exploited in extreme and harsh conditions with minimal maintenance [17].

Village electrification using PV panels as energy source can be implemented in three configurations: solar home systems (SHSs), centrally-located, and clustered systems.

i) Solar home systems (SHSs) are designed for one household. They are convenient to install one by one, but their price is too high for many households needing electricity. The cost of the first generation of SHSs was above \$350. Nowadays, the cost of a 20W SHS including solar panel, charge controller, mounting hardware, wiring, and a 600 Wh lead acid battery is approximately \$250. Solar-powered LED lanterns with wattages and storage capacities an order of magnitude lower can be packaged into a single unit costing \$25–50. These costs are affordable for considerably larger part of families without the need for financially unsustainable donation programs [18].

ii) Costs per household might be reduced by installing centrally-located solar PV systems serving for the entire village. The system can contain several solar modules (e.g. 75 W each), mounted on a self-tracking frame to increase the daily energy output by up to 40%. A centrally-located PV system's battery bank ensures reliable power supply for several days of no sunshine and has the life expectancy of 8-10 years [19]. Monitoring these systems in real conditions might provide valuable information for optimization of such lighting systems [20].

iii) In large or fragmented villages, clustered electrification using several PV-based systems might turn out to be more cost-effective.

PV-based systems for electricity supply have been introduced on commercial scale before WLEDs emerged as an attractive alternative for incandescent and fluorescence lamps.

SunLight Power Moroc, S.A. founded in 1998, in the beginning as a subsidiary of SunLight Power International Holdings, Inc. to become an independent Moroccan company in 2000 started selling PV-based systems designed to supply energy for lighting and audio-visual equipment. These power systems included battery, charge controller, fluorescent lamps, wiring and accessories (all local Products) and PV panel(s). A fee-for-service scheme has been chosen by approximately 80% of clients. According to estimates of 2001, 35% of 30 million Morocco citizens had no access to grid-based electricity, and 60% of this population could afford a solar home system on a fee-for-service basis [[21]].

In 2001, Solar Energy Supplies have been selling do-it-youself PV kits to users in the unelectrified rural areas of Zimbabwe. The systems consisted of luminaires with fluorescent or halogen lamps, wiring and switches, a charge regulator, a battery and a PV module. Running a monochrome TV was an option. The cost of a 4-light system was approximately US$ 300 in 2000 [21].

In Bangladesh, only 33% of population has access to electricity. To improve the situation, a program funded by the International Development Agency (IDA), Global Environment Facility (GEF), Kreditanstalt für Wiederaufbau (KfW), Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) and the World Bank was commenced in 2002. The target to install 50,000 solar home systems (SHS) by 2008 is considerably surpassed by now [[22]].

Implementation of systems based on combination of PV with WLED-based lamps should give a significant impact for wide-scale commercial activities. In Benin, where rural electricity coverage still stands at just 3%, United Nations Development Program (New York) in partnership with local governmental institutions and NGO implement a project on installation and maintenance of PV-based electricity supply. In 2009, subscribers pay a monthly fee of 1,500 CFA francs (US$3.50) and can light their homes, charge their mobile telephones and even have access to educational community television [21].

The village electrification using renewable energy is an important issue in China's national development. Due to expansion of regional grids and development of local hydro and other renewable energy recourses, electrification of over 95% has been achieved in China a decade back. However, these five percent of the China's population means 65 million people needing electrification. To provide electricity for these people living in unelectrified areas, the Chinese government launched a program titled Song Dian Dao Xiang in 2002. Until 2006, 964 off-grid renewable energy village power systems have been developed, including 662 PV, wind/PV, PV/Diesel hybrid systems with capacity of 16 MW, and 302 small hydro-power systems with capacity of 274 MW [[23]]. A combination of such large-scale efforts in implementation of renewable energy village power systems with China's expanding capacities in LED production, which is currently expected to outperform in volume the LED production in Japan, the number one LED producer in the world up to now, should provide a considerable progress in development of more efficient and inexpensive LED-based off-grid lighting systems.

7. Lighting alone does not make the life lighter

Even the most efficient LED-based luminaire in a house with open fire used for cooking and heating would be covered with soot within a few days. Thus, to be efficient, the implementation of solid-state lighting in remote areas of poor countries has to be carried out in parallel with solving many other problems. Smokeless metal stove to replace the open fire is one of the most important issues. Though definitely improving comfort, such a stove requires additional expenditures, which are often unaffordable for families in remote villages. Moreover, the stove has to comply with local cooking habits formed generation-by-generation by using open fire. Thus, the stove has to be customized for certain country or area. On the other hand, the stove can become a good product for local factories. Eventually, implementation of the combination of solid-state lighting and smokeless stove results in improving health conditions in the room. It is estimated that permanent indoor intoxication by smoke causes worldwide 5 million deaths yearly. Women and children, who spend more time indoor, are most severely affected.

Health issues are actually very crucial for improving the living standards in the remote villages of the developing countries. Low quality drinking water causes approximately 80% of deceases in developing world. Due to bad hygiene, the drinking water used by villagers becomes infected even in forest or mountain areas with otherwise clean springs and streams. Introduction of primitive pit latrines is quite effective for significant improvement of the situation, but also needs considerable efforts from outside and gradual dissemination from the sites, where the pit latrines are already implemented. Thus, to achieve a considerable and sustainable improvement in living conditions, the solid-state lighting has to be implemented as a part of a complex set of measures. NGO Rids Nepal, for example, addresses these issues by implementing an approach they call the "Family of Four", meaning a solar PV and LED-based lighting system, a smokeless metal stove with hot water tank, a pit latrine, and clean drinking water from a community owned spring [24]. Health care and education, even in their elementary forms, are the further indispensible ingredients of measures required for reliable and sustainable improvement of living conditions for those people, who are now on the verge of changing wick kerosene lamps for LED-based lighting.

8. Implementation and sustainability. Financial issues

Costs of a lumen-hour produced by LED-based lamps combined with solar, wind, or hydropower generators are already superior to that produced by all other lighting systems available by now and have a potential for further decrease due to technological advance and increase of the commercial production scale. Reliable components for such systems are already produced on a large scale by leading companies worldwide. Assembly of the final systems and installation is affordable for small local companies. Initial price of the systems is, however, still a big issue. Increase in income of the poor in the developing countries will enhance penetration of this technology in a natural but slow way. Financial instruments applied by local and international companies might make the process of penetration much faster. First implementations of the LED-based lighting in remote areas have been funded by international programs and served as hothouses for the emerging technology. To make the implementation sustainable, the sporadic program- and project-based funding has to be replaced by enduring, diverse, custom-friendly, but commercially viable funding schemes.

As summarized in the report of the project "Rural Energy Supply Models (RESuM)",[25] four deployment models are used in transfer or maintaining ownership of the LED-based products in developing countries:

i) *Cash.* Cash payment is usually employed in selling small systems for one household or components of larger systems. Two payment models are used. In cash & carry selling, the seller accepts no responsibilities for installation, and the customer must arrange for it. In cash sales, a contract might include installation of the product by the manufacturer company, dealer or supplier.

ii) *Credit*, i.e. a loan enabling the borrower to purchase the product. Ownership of the product is transferred to the customer when the contract is signed. In rural areas in developing countries access to credits is usually difficult and interest rates are very high due to low creditability of customers, high inflation rates, political instabilities etc.

iii) *Leasing.* In leasing agreement, the lessor, who owns the property, allows the client (the lessee) to use the property for a specified period of time in return for payment. Ownership may be transferred to the user after the leasing period.

iv) *Service.* The product is supplied by a service provider to the user as a service in return for payment. The ownership is retained by the service provider.

The choice of the most appropriate model depends on local conditions. Commercial companies consider the choices as usual business decisions. Governments of the developing countries can influence the process and improve financial conditions for implementation of the solid-state lighting. Meanwhile, development in technology makes the lighting systems less expensive and provides better chances for their penetration in the areas inhabited by people with low income.

9. Conclusion

In conclusion, LED-based lighting is a promising and already cost-effective lighting technology for implementation in remote areas of developing countries. Technical issues of the further development of the technology basically coincides with those important for general on-grid LED-based lighting, though some specific aspects might be purposefully addressed to make the product more cost-efficient. Currently, the implementation of the new lighting technology is on the stage of the dissemination of awareness on availability and first demonstrations in action. Transition to the next step, i.e. to commercialization on a broad scale, will depend rather on education, state policies, and entrepreneurship, than on basic technical issues, though increase in LED efficiency and adaptation of the LED-based lighting systems to conditions and requirements of their use in remote areas will accelerate this transition.

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