SOLAR POWERED LED LIGHTING –
HUMAN FACTORS OF LOW COST LIGHTING FOR DEVELOPING COUNTRIES

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ABSTRACT: Lighting, communication and water supply are generally considered to be the major domestic applications of PV systems in rural areas in developing countries. Though at present most solar powered lighting systems and solar lanterns use compact fluorescent lamps (CFLs), current market prices and long-term technology roadmaps of light emitting diodes (LEDs) indicate that white LEDs might become a serious alternative for CFLs in PV applications. Since PV powered LED lighting will be dominantly applied in a domestic setting, our paper strongly focuses on human factors of lighting. It is argued that an acceptable minimum requirement for the illumination level of domestic lighting could be 30 lux. For this reason a 1 Watt LED connected to a small PV panel of typical 1 Wp could provide enough electricity for three to four hours of lighting in most of the developing countries. Such a small PV powered LED lamp including a rechargeable battery would have a retail price of 12 up to 16 $. Our paper demonstrates new opportunities for affordable and mobile lighting systems and is illustrated by conceptual designs of PV-powered LED lighting systems for the case of Cambodia.
Keywords: PV System, Developing Countries, Lighting, Design

1 INTRODUCTION

At present most PV powered lighting systems and solar lanterns use compact fluorescent lamps (CFLs) or fluorescent tubes [1-4]. They are appropriate for the circumstances of use [3], but PV powered CFLs are still rather expensive [4]. Moreover once disposed of, CFLs generate waste with toxic elements such as mercury.

White LEDs might become a serious alternative for CFLs in PV applications. The white LED is highly energy-efficient, it can meet the minimum requirement for lighting levels of visual tasks, it cuts down costs of lighting considerably and is durable compared to other electric light sources. Moreover, LEDs are operated at low voltage levels in the order of several volts, for which reason their energy requirement can be easily met by small battery-based PV systems. The use of light emitting diodes (LEDs) in stand-alone battery-based PV systems might both reduce costs and environmental impact of lighting. As well as that, LEDs could meet the requirements for visual task lighting which we will specifically discuss in this paper.

Until now only little has been reported about PV powered LEDs [5-7]. Two papers cover the field of high power lighting for industrialized countries [5-6]. A comprehensive study on rural lighting in China [7] compares LEDs with other light sources, but does not pay attention to the human factors of PV power LEDs to meet the need of durable, cheap and mobile lighting of inhabitants of rural areas in developing countries [8-9].

In Section 2 we will first discuss the human factors of lighting from a theoretical point of view. Next in Section 3 we will apply our findings to LED lighting and more specifically in Section 4 to solar powered LED products in the framework of costs and other options for autonomous lighting. Adding to this, Section 4 shows some examples of product designs with PV powered LEDs. We will complete our paper with conclusions in Section 5.

2 HUMAN FACTORS OF LIGHTING

2.1 Social aspects of lighting

A considerable part of the world's population struggles with poverty. This situation is characterized by lack of access to education, health care and infrastructure, such as clean water supply and electricity. Lighting, clean water and communication are considered basic assets in developing countries. Each of them is directly or indirectly depending on access to electricity. Lighting is required for education, improves the security of communities and advances productivity [10]. Therefore access to affordable domestic electric lighting could contribute considerably to the development of low income groups. Since reliable electricity supply from the grid is not sufficiently available in most rural areas of developing countries, particularly electric lighting which is operated autonomously can contribute to local development.

2.2 Visual perception of light

Lighting serves two purposes [8]:

1) to perform visual tasks (functional lighting),
2) to enliven the surroundings (amenity lighting).

Amenity lighting covers the aspects of the quality of the lighting and relates to aspects of communication and aesthetics of lighting.
Functional lighting primarily covers aspects related to the quantity of the lighting, such as reading and writing performance. In our paper we would like to focus on functional lighting and the perception of visual information.

Therefore we will first shortly explain some technical lighting terms related to visual performance, i.e. the ability to perform a visual task.

- *Illuminance*, E, describes the amount of light falling onto the task. It is expressed in lux.
- The light reflected by the task object makes it bright. Brightness is quantified by the *luminance*, L, of

an object, which is expressed in cd/m^2.

- *Contrast sensitivity* is the ability to see small differences in brightness e.g. different shades of grey.
- *Visual acuity* is the ability to see small details, e.g. small print. The visual acuity usually is expressed in the reciprocal of the object size, expressed in minutes of arc. For instance a visual acuity of 1.0 corresponds to an object of 1 minute of arc, a visual acuity of 1.4 with an object of about 0.7 minutes of arc.
- Also variables such as *glare* and *colour rendering* are used as technical terms for lighting.

Details may be found it textbooks of illuminating engineering [11-12].

2.3 The minimum illumination level required for reading

Lighting is essential to allow the perception of visual information. Each visual task has its own requirements for visibility. It can easily be observed that almost all aspects of visual performance depend on the ambient lighting level. The ambient lighting is the adaptation level, and is commonly expressed in luminance values. In order to find the minimum requirements for domestic lighting, we refer to two basic studies: one by Blackwell related to the contrast sensitivity [13] and another by Lythgoe related to the visual acuity [14]. In course of time many additional studies have been done providing more valuable details about visual performance, however they haven't disproven the basic results shown in Figure 1 and 2.

In Figure 1 the relation between the contrast sensitivity and the adaptation level is depicted. In this figure it is shown that -with a probability of 95 % - a contrast of 40 % still can be discerned at 1 cd/m^2, a contrast of 20 % at 4 cd/m^2 and 10 % at 35 cd/m^2. Printed matter with a high quality has a contrast of 80 %; 40 % contrast or below relates to black letters at grey paper or letters with faint borders. This means that contrast of well-printed matter can be perceived at very low adaptation levels. Also, it seems that the contrast sensitivity, at least for young adults, is hardly a limiting factor for domestic lighting.

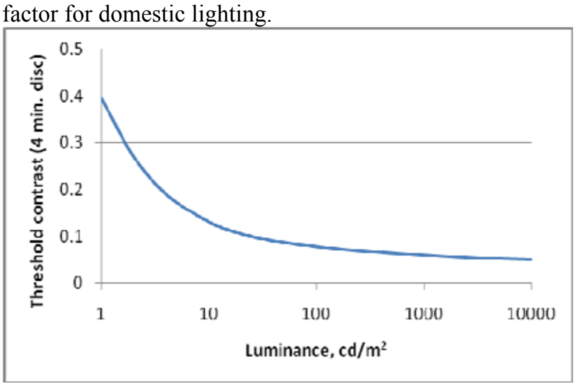

Figure 1: **The relation between the contrast sensitivity and the adaptation level based on [13].**

The second study we will apply regards the relation between the visual acuity and the adaptation level as shown in Figure 2. Here it is found that at an adaptation level of 5 cd/m^2, a visual acuity of about 1.4 can be reached. For a normal reading or writing task, a visual acuity of about 1.0 usually is considered as adequate. So we may consider 5 cd/m^2 an adequate luminance for the purpose of reading printer matter.

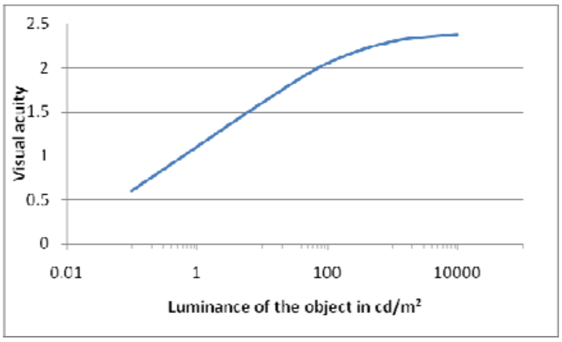

Figure 2: **The relation between the visual acuity and the adaptation level based on [14].**

It is customary to express the yield of a lighting installation in terms of the illuminance on the working plane. Here we will use the following basic relation between luminance, L, illuminance, E, and reflectivity, ρ, for diffuse (Lambertian) surfaces such as paper:

$$E = \pi \cdot L / \rho \qquad (1)$$

An average reflectivity of 50% - a rather low value for arbitrary white writing paper – and a luminance of 5 cd/m^2 requires an illumination level of about 30 lux. Thus, we will consider 30 lux as the minimum requirement for domestic lighting for reading or writing tasks by young adults. Individual differences might affect this value. Particularly, age is a matter of concern regarding illuminance levels.

The influence of age on visual perception depends on many factors among which physical deterioration of the eye and decrease of speed of reaction. For this reason the required illuminance depends on age, and the value of 30 lux given above should be used with caution. Figure 3 from [9] shows the relation between age and relative required illuminance, indicating that the older a person, the more light is required for visual tasks. It implies that for people aged 50 more than 3 times as much illuminance is required for a continuous visual task such as reading, i.e. 100 lux instead of 30 lux. Above all, from Figure 3, can be concluded that at low illuminance children's visual perception is excellent compared to mid-aged adults.

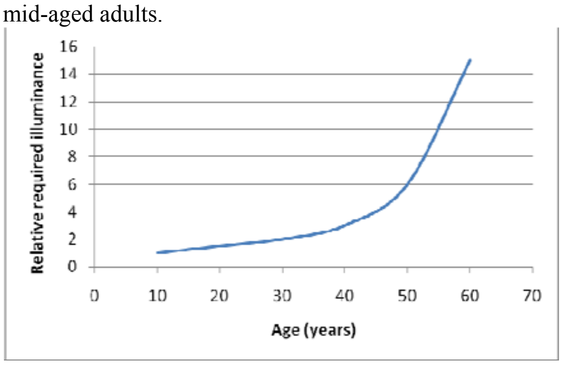

Figure 3: **The relation between age and relative required illuminance from [9].**

2.4 Comparison with standards for illuminance

According to standards of CIE [15] recommended illuminance for indoor lighting in between 300 and 1000 lux for selected tasks. Compared to these standards our value of 30 lux might seem low. This is mainly explained by the fact that the CIE standard focuses on office lighting in industrialized countries, where cost aspects are usually considered less important than factors of user amenity and architect satisfaction. CIE recommendations are derived from visibility tests on mid-aged persons in office environments. The aim of office lighting is to create an atmosphere of amenity and comfort, in which office workers may work for many hours at a stretch on a daily basis for many years.

CIE standards for outdoor lighting [16] recommend illuminance of 2 to 3 lux for residential streets with low traffic. This light level is sufficient to discern small objects, like stones, but it won't meet the requirements for reading. Despite this, most persons are satisfied with this amount of light.

Still no international consensus exist about recommended lighting levels for selected tasks according to an international comparison of lighting standards: 10-fold variation is a common number within one task [17].

3 PV-POWERED LEDS

3.1 LEDs

A light-emitting diode (LED) is a semiconductor diode that emits light when an electrical current is applied in the forward direction of the device. The effect is a form of electroluminescence where incoherent and narrow-spectrum light is emitted from the p-n junction. Most LED are made from hetero-junctions of III V compounds containing elements such as Ga, As, Al, In and P. For this reason LEDs are operated at low voltages of 1.9 Volt (for red light LEDs), 2.2 Volt (green LEDs) and 2.6 Volt (blue LEDs). A white light LED (W-LED) is made by combining several monochromatic emitters; for instance a trichromatic monolithic W-LED comprises both red, green and blue light emitting zones, a dichromatic W-LED combines a yellow and blue light source. Since for reading purpose white light is required, we will further only refer to W-LEDs when we use the term LED in our paper.

The energy conversion efficiency of LEDs is high, resulting in a high efficacy. The luminous efficacy of lighting, η, is defined by:

$$\eta = \Phi_v / P \qquad (2)$$

where Φ_v is the luminous flux (in lumen) and P the power consumed (in Watt) The efficacy of LEDs in the market ranges from of 15 to 60 lm/W, where 50 lm/W is considered a well-performing LED.

It is rare for a LED to fail completely. Instead the intensity of light emitted slowly decreases over time. 70 % of lumen maintenance is close to the threshold at which the human eye can detect a reduction in light output. For this reason the time towards 30% reduction of a LED's light output is considered a measure for its useful lifetime. This standard is named L70 and is in the order of 30.000 to 100.000 hours. Generally it's found that low junction temperature and a low forward current positively affect the LED's lifetime.

According to the Shockley diode equation the forward current flowing through a LED will increase exponentially with the voltage applied. Since a LEDs lifetime can be reduced considerably by continuous high currents, a LED has to be operated with a driver, an electronic device which applies either a constant current or pulses of higher currents.

Because of the relatively high refraction index of III V materials, a LED with a flat surface produces a forward directed light bundle with a maximum angle of 120°. Other geometries, like hemispherical and parabolic surfaces, result in respectively larger emitting angles and directional light.

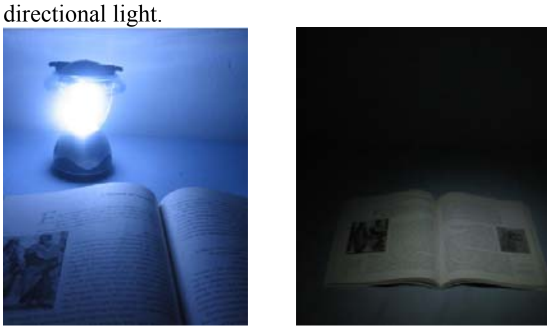

Figure 4: **Light distribution over printed matter by ambient light (left) and by directional light (right).**

3.2 LED lighting needed for reading

Based on the illumination level of 30 lux which is considered the bare minimum requirement for domestic lighting for reading or writing tasks by young adults, a LED light can be selected. LEDs provide directional light instead of ambient light, see Figure 4. Furthermore we assume that homework handiwork is done at a table with a height of 0.8 m while sitting on a chair. The work area has an active radius of 0.35 m. This corresponds to a useful area of about 0.25 m^2 The LED lamp will hang above the centre of this area at a height of 0.7 m. As a result, shown in Figure 5, the rim of the lit area makes an angle of 27 degrees with the downward vertical through the lamp. From basic photometry, it follows that the luminous intensity, I, of the lamp, directed to the rim of the working area, is 42 cd at illuminance of 30 lux (i.e. 30/tan 27°). In the centre of the working area, the luminous intensity will be slightly higher, and so will be the illuminance.

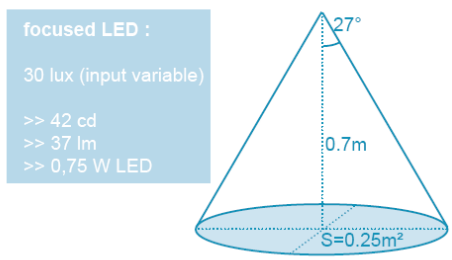

Figure 5: **The lighting geometry for sizing of a LED light which provides 30 lux of illumination.**

The final step is the assessment of the required luminous flux, Φ_v, which is related to the luminous intensity, I, by:

$$\Phi_v = I \cdot \Omega \qquad (3)$$

where Ω is the solid angle of the emitted light.

A LED provides directional light. Particularly, modern LEDs are delivered with a protecting cover that acts as a collimator lens which creates a light bundle. The corresponding solid angle of the lighting geometry shown in Figure 5 is 0.9 steradian. Therefore, the required luminous flux for a LED would be 37 lumen (i.e. 42 cd · 0.9 sr). Assuming an efficacy of 50 lumen per Watt, a LED of 0.75 W would be a bare minimum to meet a lighting demand for reading of 30 lux.

It might be mentioned here, that the precise photometry of LEDs is still a matter of study [19].

3.3 LEDs energy consumption compared

In developing countries the following lighting options are common: wax candles, stearine candles, kerosene lamps, incandescent lamps and fluorescent lamps. Table I compares LEDs with these options for lighting in relation to the requirement to meet a lighting level of 30 lux according to the geometry shown in Figure 5.

A conventional incandescent lamp is an isotropic light source which emits light in all directions. Using formula 3 with $\Omega = 4 \cdot \pi = 12{,}6$ sr, an incandescent lamp should need a luminous flux of 530 lm to meet the required light intensity of 42 cd. Conventional incandescent lamps have an efficacy of about 12 lm/W. For 530 lumen, one would therefore need 0.73 lamps of 60 W, which requires a power of 44 Watt, see Table I.

From Table I it can also be concluded that electric lights sources, i.e. incandescent, fluorescent and LED lamps, can easily meet the required illuminance of 30 lux, Lighting based on combustion, i.e. candles and kerosene lamps, can't, and multiple lighting units are required to reach the required level of illumination. Since the efficacy of these light sources is extremely low, the total power needed to meet 30 lux is considerably exceeding that of electric lamps.

Besides this, among the electric light sources the LED appears to be highly energy efficient, since the power need of incandescent and fluorescent lamps exceeds that of LEDs, yielding a higher total power consumption at 30 lux.

Table I: Characteristic power, luminous flux and efficacy of light sources. Fuel consumption of kerosene lamps given in liter per hour; information of candles from [19]; information from stearine candle from [20]; information of incandescent lamps and fluorescent lamps from Philips.; The two most right columns refer to the number , N, of lighting units and the total power, P_{tot}, that are needed to fulfil a task lighting need of 30 lux on an area of 0.25m^2.

Lamp	P *(W)*	Φ_v *(lm)*	η *(lm/W)*	N	P_{tot} *(W)*
Wax candle	55	1	0.02	530	29.2k
Stearine candle	80	10	0.125	53	4.2k
Kerosene 0.02 l/h	200	10	0.05	53	10.6k
Kerosene 0.05 l/h	488	100	0.21	5.3	530
Incandescent GLS	60	730	12	0.73	44
Fluorescent PLE *	11	600	54	0.88	10
White LED 50º	**0.75**	**50**	**50**	**1**	**0.75**

*) including ballast

4 PV-POWERED LED PRODUCTS

4.1 Description of PV-powered LED products

A PV-LED product consists of one or more LEDs, a rechargeable battery and a small PV module. The system is controlled by electronics among which a charge controlling unit for the battery and a LED driver. The electrical components are incorporated in a casing with a user interface which allows operation of the product. The LED lamp itself is embedded in a luminaire which often has an aesthetically pleasing appearance. However it actually must meet several technical requirements: physical protection of the lamp and control and distribution of the light from the lamp. Here one can think about reflectors and color filters.

4.2 Costs of PV-powered LED products compared

A small PV panel of typical 1 Wp could provide enough electricity for three to four hours of lighting by a 1 W LED in most of the developing countries. The retail price of a small PV powered LED lamp including a rechargeable battery of up to 10 Wh would be in the order of 12 up to 16$. Compared to CFL based PV lanterns which cost about 60 to 80$ such as LED lamp is reasonably cheap. However compared to a kerosene lamp of 1$ it's still a relatively high investment for poor families.

After purchase, operating costs determine the costs of ownership of a certain option for lighting. Here we refer to the methodology developed by Jones et al [21]. Costs of operation comprise replacements of spare parts and costs of energy to power light, such as electricity for grid-connected (GC) lighting and fuel for kerosene lamps. Figure 6 presents for several lighting options the costs of ownership. It shows that grid-connected lighting is the cheapest option with 0.04$/1000 lux-hours, but because access to the electricity often lacks, autonomous options for lighting have to be used. Figure 6 shows that kerosene lamps have very high costs of ownership of 12.00$/1000 lux-hours, mainly due to fuel consumption. Halogen flashlights with costs of 3,40$/1000 lux-hours require frequent replacement of primary batteries. The costs of ownership of a rental lamp called Proseed comprising a 1 Watt LED and a rechargeable battery are mainly due to the rental costs. A 1 Watt PV-LED lamp is the cheapest option of two PV-powered lamps shown in Figure 6. With costs of ownership of 0.22$/1000 lux-hours, it's the cheapest option for autonomous lighting available.

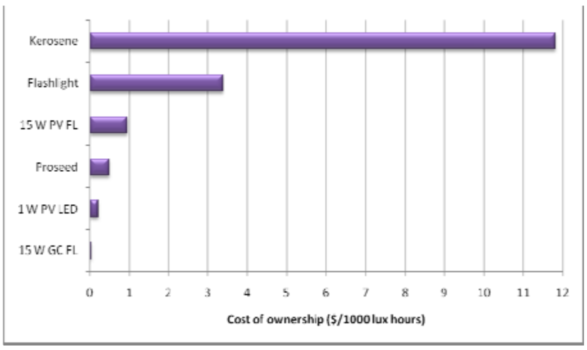

Figure 6: **The costs of ownership of different options for rural lighting in $/1000 lux-hours assuming 3 hours of lighting each day, data taken from Cambodia 2007-2008.**

4.3 Design of PV-powered LED products

Given their energy efficiency, high efficacy, reasonable purchase costs and low costs of ownership, it would be worthwhile to design product concepts for PV-powered LEDs. Adding to ongoing activities [22] of the company Kamworks, conceptual designs of PV-powered LED products have recently been developed by a team of students industrial design engineering (IDE) from TU Delft [23] and a student IDE from University of Twente [24] in the Netherlands.

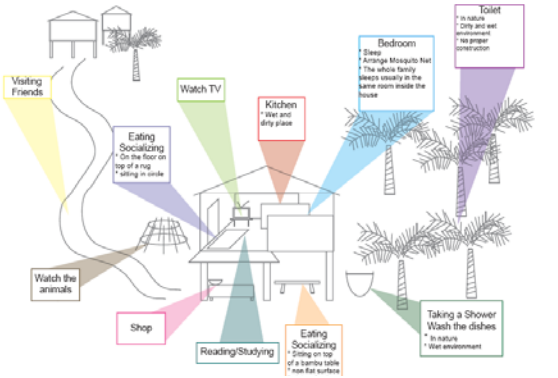

Figure 7: **Domestic use of lighting in rural areas in Cambodia.**

In the design projects the mission statement of Kamwork is reflected; to provide affordable sustainable energy systems in Cambodia and to locally manufacture affordable solar products.

The following target groups were taken into consideration: the lowest social class is defined by earnings less than 1,50 $/day, the upper social class are considered rich with a daily income of 3,00 $/day. Members of the middle social class earn 1,50 to 3,00 $/day. From these findings it might be clear that the lamp should fit low-income consumers and target the so-called Bottom of the Pyramide – BOP - market By means of interviews and observation the circumstances of use of the lighting product were investigated. Figure 7 shows the resulting overview of activities related to domestic use of lighting in rural areas in a developing country.

In relation to these activities specific product attributes for the circumstances of use could be identified: the lamp should be portable. When needed the product should be used free-handed. It should be placed on a table or hanged from the ceiling, walls or other building constructions. The product should provide enough luminosity to be able to read. The LED lamp should be shock, water and dirt resistant.

Figure 8 shows a concept of a PV-powered LED product [24] which targets the upper social class. Since nine high efficacy LEDs have been incorporated in the luminaire, obviously it provides a high luminosity (estimated 370 lm). The luminaire can be used both in a hanging and standing position. However, due to a separate battery unit this product concept does not meet the requirement of mobile use.

Figure 9 shows a product concept of a portable PV-powered LED lamp [23]. The strap represents the most crucial handling feature allowing to wear it comfortably and to easily connect the product to building constructions. The upper shell is semi-transparent to diffuse the bright LED light, hiding at the same time inner components such as the batteries and electronics. Using it at full power the product delivers about 42 lm by 6 low efficacy LEDs (7 lm per LED) during 3.5 hours. In dimmed mode it produces diffuse – amenity - light for 6 hours. Estimated retail price of this PV-powered LED product will be in the order of 12 to 16 $.

Figure 8: **Artist impression of a conceptual design of a PV-powered LED product [24], including PV panel, battery unit and luminaire in hanging (left) and standing (right) position.**

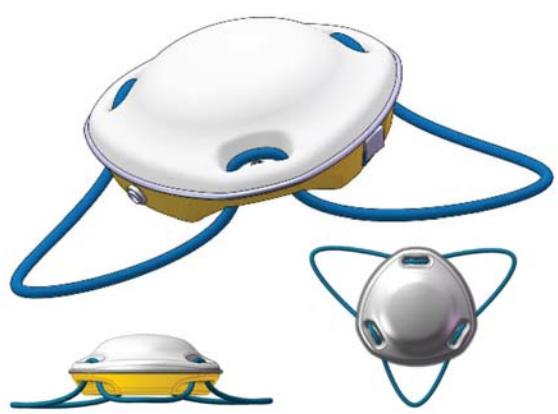

Figure 9: **Artist impression of a conceptual design of a portable PV-powered LED product with strap [23]. PV panel not included in the rendering.**

5 CONCLUSIONS

Our paper demonstrates new opportunities for affordable and mobile PV LED lighting systems and is illustrated by conceptual designs of PV-powered LED lighting systems for the case of Cambodia. In our paper is argued that an acceptable minimum requirement for the illumination level of domestic lighting could be 30 lux. For this reason a 1 Watt LED connected to a small PV panel of typical 1 Wp could provide enough electricity for three to four hours of lighting in most of the developing countries. Such a small PV powered LED lamp including a rechargeable battery would have a retail price of 12 up to 16 $ and low costs of ownership compared to other options for autonomous lighting.

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7 REFERENCES

[1] Muhopadhyay, K., Sensarma, B. and Saha, H, Solar Energy and Materials and Solar Cells 31 (1993) 437.
[2] Mukerjee, A.K., Energy Conversion & Management 41 (2000) 621.
[3] Reinders, A.H.M.E., Pramusito, Sudradjat, A., Dijk, V.A.P. van, Mulyadi, R. and Turkenburg, W.C., Renewable & Sustainable Energy Reviews 3 (1999) 1.
[4] Gullberg, M., Ilskog, E., Katyega, M. , Kjellström, B., Energy Policy 33 (2005) 1287.
[5] Grzesiak, W., Ciez, M., Zaraska, W., Proceedings of 20th European Photovoltaic Solar Energy Conference, (2005) 2192.
[6] Bican, P., Libra, M., Poulek, V. Proceedings of 20th European Photovoltaic Solar Energy Conference, (2005) 2663.
[7] Jones, R., Du, J., Gentry, Z., Gur, I. and Mills, E,, Proceedings of Right Light 6 (2005).
[8] D.A.Schreuder, Proceedings of UNESCO - A world of science (2005).
[9] D.A.Schreuder, Proceedings of NSVV Nationaal Lichtcongres (2004)
[10] Ramani, K.V. and Heijndermans, E., 'Energy, Poverty and Gender, a synthesis', The World Bank (2003).
[11] Hentschel, H.J., 'Licht und Beleuchtung; Theorie und Praxis der Lichttechnik', Germany (1994)
[12] Schreuder, D.A., 'Openbare verlichting voor verkeer en veiligheid', Kluwer Techniek (1996)
[13] Lythgoe, R.J., Medical Council Special Report No. 175. London. H.M. Stationery Office (1932).
[14] Blackwell, H.R., Journal of the Optical Society of America 36 (1946) 624.
[15] CIE, Publication No 29.2 (1986).
[16] CIE, Publication No 115 (1995).
[17] Mills, E. and Borg, N. Journal of the Illumination Engineering Society of North America, 28(1) (1999) 155.
[18] Mills, E., IAEEL Newsletter 9 No 2 (1999) 2.
[19] CIE, Publication X022 (2001).
[20] Vermeulen, J., Personal communication with D.A.Schreuder, (2000).
[21] Jones, R., Du, J., Gentry, Z., Gur, I., Mills, E., Proceedings of Right Light 6 (2005).
[22] Reinders, A., Gooijer, H. De, Diehl, J.C., Proceedings of 17th PVSEC (2007).
[23] Alvarez, A., Papantoniou,L., Wirth, S., Wouw, D. van der, Affordable Lighting for rural Cambodia, Integral Design Project, TU Delft (2008).
[24] T. Gorter, Affordable PV-LED lighting for rural Cambodia, Internship report, University of Twente (2008).