SOLAR LANTERNS FOR REMOTE AREAS

Salinee Tavaranan
John Duffy
University of Massachusetts Lowell
1 University Avenue
Lowell, MA 01854
Salinee_Tavaranan@student.uml.edu
John_Duffy@uml.edu

ABSTRACT

Lighting appears to be the most sought-after application when solar electricity first reaches a remote village. Solar lanterns increase living standards, enhance education, provide extra time for productive work during the night, initiate rural development, and improve health and usually save money compared to kerosene lanterns. This study begins with the gathering of research findings based on solar lanterns and rural lighting as well as the component selections of a new solar lantern design that would improve the quality of light and enhance performance to meet standards for area and reading lighting. Experiments were performed on four commercial lanterns and generated data on the light output, charging and discharging performance. A prototype was designed and fabricated based on light intensity and duration, and cost. The results from prototype testing show that the new design meets user requirements and improves the light quality compared to the four tested lanterns. Results are encouraging of incorporating new technologies: dye-sensitized solar modules, and in headlamps: ultracapacitors, and light emitting diodes (LED)..

1. INTRODUCTION

Solar powered systems have a great potential for improving the quality of life, as well as market potential, in developing countries. Most solar systems in developing countries are standalone systems, such as for solar streetlights, domestic lights, lanterns, vaccine refrigerators, water pumping and purification systems, computers for education, etc.

It is estimated that there are two billion people in the world without access to electricity (11). A basic and high priority need among people all over the world is lighting. The rural areas of developing countries generally use kerosene wick lamps, candles, or hurricane lanterns to provide lighting (5). The light quality of these sources is very poor (10-15 lumens for wick lanterns and 40-50 lumens for hurricane lanterns) (12). Light in these households is used mainly to see contours and prevent people from bumping into each other or into furniture, and is not bright enough for reading, studying or doing other productive tasks.

The promising alternative lighting provided by solar photovoltaic power could increase the quality of life by providing good quality light for education and extra work during the night while minimizing air emissions that can create health problems such as asthma.

2. SOLAR LANTERN DESIGN

2.1 Product Design Specifications

The basic design goal is to produce a lighting unit that provides healthy area lighting in remote households where there is no access to the electric power grid. The important features of the design were identified as followed:

- Maximum price of the unit no more than $75
- Provide 5-hour minimum operating daily usage
- Have sufficient amount of area lighting
- Have low and high voltage disconnects
- Minimum 5 years of overall system lifetime
- Unit mass should be no more than 4 kg

2.2 Component Selections

2.2.1 Lighting

According to ECN[1], for reading the minimum illuminance of about 50 lux (or 5 footcandles) is required, for general area lighting 20-25 lux (or 2-2.5 footcandles) is sufficient

(13). Lights with a lumen output of less than 20 lux are suitable only for orientation lighting (7).

There are no consistent criteria among countries as to the “right” level of light for a specific task; even within a given country over time standards have changed. Recently recommended illuminance levels in the several countries tend to converge at levels significantly lower than those existing in recent decades. For the designs in this study, the ECN standards (7) are used both for area lighting (25 lux) and reading task light (50 lux).

Compact fluorescent lights (CFL) are the most energy efficient for area lighting (50-100 lumens/W). Standard CFLs operate best with tube downwards (or in a base up) position. The light output decreases by up to 15 – 20 % in a base down position because the excess mercury drips from the cold spot at the top of the lamp into the hot gas tabulation in the base where it is revaporized (6).

Area Lighting Design

To calculate the lumens needed to give an adequate amount of light, the following equations are considered:
The inverse square law defines the relationship between the irradiance (I) from a point source and distance. It states that the intensity per unit area (E) varies in inverse proportion to the square of the distance (d).

$$E = I / d^2$$

The more convenient alternate form is:

$$E_1(d_1)^2 = E_2(d_2)^2$$

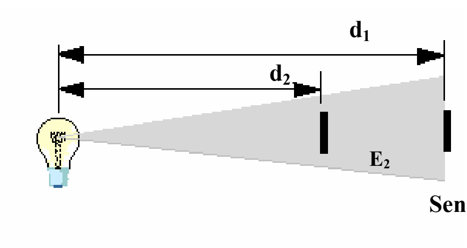


Fig. 1: Inverse Square Law

Since the adequate intensity for area lighting is 2.5 footcandles or 25 lux approximately at the surface area of activity, which is assumed to be at 3 feet away from the light source, the lux (lumens per square meter) needs to be converted to the lumens the bulb needs to produce based on the distance from the light source to the task surface, by the following procedures:

Calculate the irradiance at 1 meter.

1) Convert from lux (lm/m^2) to lumens / steradian (lm/sr) at 1 meter):

$$E_{1.0m}(lm/m^2) * 1m^2/sr = E_{1.0m}(lm/sr)$$

2) Calculate the solid angle[2] of the lamp in steradians, with the base block angle[3] at 30 °

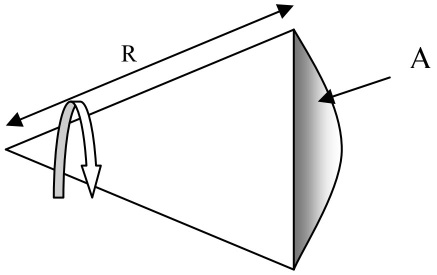


Fig. 2: Solid angle $\Omega = A / R^2$

α is the angle that light actually gives out or base block angle

$$\Omega = A/R^2 = 2\pi(1-\cos(\alpha/2))$$

3) Calculate the total lumen output:

$$E_{1.0m}(lm/sr) * \Omega(sr) = Output(lm)$$

The needed light intensity from the lamp is 273 lm from calculations with the above equations to provide 2.5 fc at 3 feet in all directions. In addition, as a reconfirmation of this result, the ESMAP[4] surveys showed that the light output of 200-300 lumens from a 5 watt compact fluorescent lamp (CFL) or a 6 watt tubular fluorescent lamp (TL) is considered to be an adequate option while 160-200 lumens from a 4 watt TL is not. A lantern with 6 watt TL and a modified ballast to reduce the power consumption to 3 watts was not considered since it compromised the quality and light output (11).

A 5-watt fluorescent lamp with the color temperature close to the daylight was selected for this lantern design.
To design the lighting, it is important to focus not only on the lumen output but also color, lifetime, availability, and cost.

2.2.2 Photovoltaic Module

Photovoltaic modules or solar panels are semiconductor devices that convert part of the incident solar irradiation directly into electrical energy. The photovoltaic technologies have been dominated by solid-state junction devices, most made of silicon.

Dye-Sensitized Nano-Scale Solar Cells

Unlike conventional solar cells, the dye-sensitized solar cells’ foundations are in photochemistry rather than in solid state physics. The concept of dye-sensitized solar cells has been known for a period of time, but the 1990's breakthrough in the Swiss Federal Institute of Technology made commercialization possible. The structure of a dye-sensitized solar cell is comprised of a transparent conducting electrode coated with porous nanocrystalline titanium dioxide (nc-TiO_2), dye molecules attached to the surface of the nc-TiO_2, an electrolyte containing a reduction-oxidation couple, usually I^-/I_3^- and a catalyst coated counter-electrode. On illumination the cell produces voltage over and current through an external load connected to the electrodes (3) as shown in Fig. 3. Other cell designs are also possible, i.e. plastic can also be used as a substrate material or a monolithic design can be applied (10).

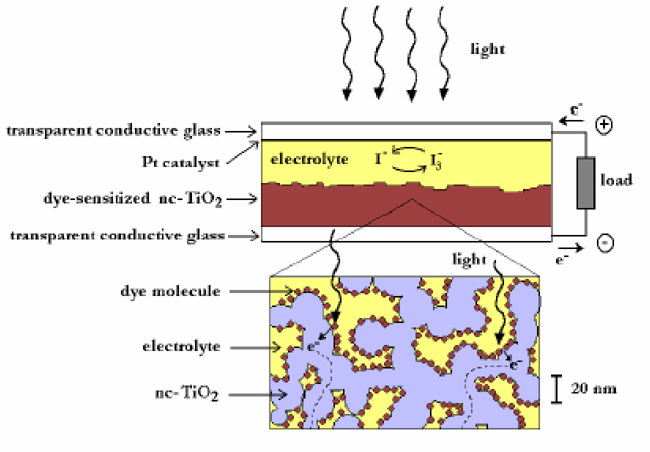


Fig. 3: A schematic representation of the structure and components of a dye-sensitized solar cell (3).

PV Sizing

The size of PV module (in peak watts) corresponding to a given power rating of the CFL (in watt) may be estimated from the following simple relation:

$$W_P = \frac{W * h / day}{ESH * \eta_b \eta_{cc}}$$

W_P = solar module peak watts (in Watts)
W = power rating of CFL (in Watts)
h = daily usage (in hours)
ESH = equivalent sun hours, global annual mean daily solar irradiation (kWh/m^2/day)
η_b = battery efficiency
η_{cc} = charge controller efficiency

The selected CFL rated input power is 5 watts. According to the design criteria, the daily usage is 5 hours. The global annual average ESH (Equivalent Solar Hours) chosen is 4 hours (1). Battery efficiency and charge controller efficiency were assumed to be 90% and 85%, respectively. The PV sizing result turns out to be an 8.2-watt panel.

2.2.3 Battery

Several types of rechargeable batteries were considered for this project. The main battery chemistries that were examined are valve regulated lead acid, nickel cadmium, nickel metal hydride and lithium ion.

According to the studies of gel type VRLA (9) and (4), the designs of cells give encouraging performance during operation under simulated RAPS (Remote Application Power Supply) duty. This type of duty cycle is based on low discharge rates and depth of discharge. The gel-type VRLA batteries are suitable for solar applications and the use for a rigorous, and irregular, cyclic charge-discharge process.

Many lights and small applications can be found using 12 volt DC rated system voltages and efficiencies are high. On the down side, 12 volt systems suffer from high line loss problems, compared to higher voltage systems. The PV modules cannot be far from the battery bank. Since the solar lantern system is a small application and the wiring will not be too long, a 12 volt system is suitable for the design. Therefore, the 12-volt VRLA battery has been chosen for this lantern design because it is the most common and least expensive appropriate technology for solar applications.

Battery Sizing

The battery storage capacity S in ampere hours (Ah) may be estimated as:

$$S = \frac{W * h * N_S}{V_b * \eta_b * \eta_i}$$

W = power rating of CFL (in Watts), 5 watts
h = daily usage (in hours), 5 hours
N_S = the number of days of storage (in days), 2 days
V_b = battery voltage (in volts), 12 volts
η_b = battery efficiency, assumed to be 90 %
η_i = inverter efficiency, assumed to be 85 %

If the backup storage is two days, from the calculation the battery capacity should be 5.5 Ah or higher.

2.2.4 Charge Controller

The basic function of the charge controller is to prevent the battery from overcharging. In addition, there are several other functions that the charge controller can be used for, for example, low voltage load disconnection or switching the energy to be used for an auxiliary load (i.e. radios). The other consideration is to size charge controllers for the peak operating conditions. The failure occurring because of undersized controllers can cost more than an initially oversized charge controller.

A less expensive charge controller uses shunt type switching since it requires less electronics. Furthermore, there is less voltage drop while charging. However, the disadvantage of shunt switching is that the circuit has to handle conservatively full solar module current (I_{sc}) when the switch short circuits the panel. This causes more heat inside the controller. Not only will the controller handle the peak current from the PV module, it will have to be sized by a safety factor. Basically, PV modules are rated maximum power at standard conditions (1000 W/m^2 irradiation and 25 °C module temperature) but at other conditions the module performance may be higher than the rated values. Therefore, the charge controllers have to be determined by the safety factor of 1.4 for typical PV systems (2).

The simplest charge controller circuit with high and low voltage disconnect is selected for this lantern design. Ideally, the most suitable charge controller for sealed VRLA battery applications is the series-linear, constant-voltage and pulse width modulated (PWM) design. For a small PV system, component cost affects system capital cost drastically; thus the more expensive series and PWM controllers are out of the question for the lantern design.

3. PROTOTYPE FABRICATION AND TESTING

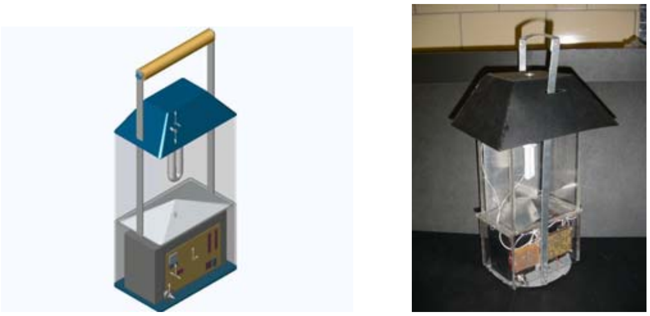
3.1 Lantern Assembly

The part that holds the weight of the lantern is the base; therefore, the handle needs to be attached to the base somehow. The lantern drawing shows the handle attached to the top part of the battery housing and battery housing is connected to the base of the lantern (three dimensional drawing in Fig. 4(A)). For prototype fabrication, the handle is directly attached to the base as seen in Fig. 4(B).

The well-designed luminaire (and housing) with a reflector can cut power needs by almost half. The material for housing should have good heat transfer properties and high transmittance. If the ventilation is not adequate, the operating temperature can be higher than it was designed for, resulting the lesser lighting output than it should.

3.2 Prototype Testing

Four commercial solar lanterns were tested to compare the results with the new designed lantern.



(A) (B)

Fig. 4: Lantern assembly. (A) three dimensional assembly. (B) Actual prototype, handle attached to the base.

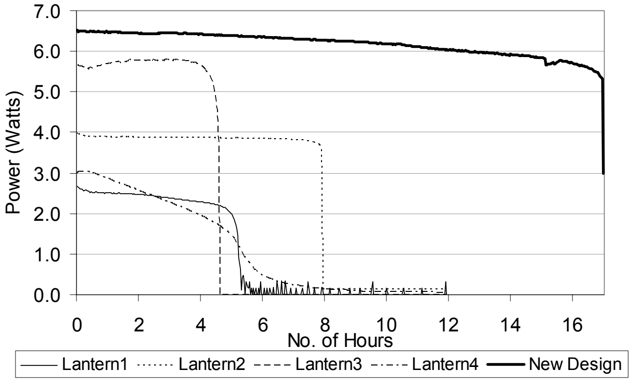


Fig. 5: Power consumption of the new lantern compared to the other 4 lanterns.

The power consumption of all lanterns including the prototype is shown in Fig. 5. Even though the new design consumed the highest power, the light level meets the ECN standard at 3 feet away from the source and the usage hours are up to 17 during this discharge cycle.

3.3 Cost Analysis for Prototype

The cost of each lantern component was considered from the wholesale price. To estimate the sale price of the lantern system, an additional 30% of the total component cost is included as manufacturers and distributors profit or manufacturing cost.

The design meets most of the specifications, but the estimated price of the system is more expensive than the specification stated. For people from developing countries, they might not be able to afford this price. In order to adjust the system price substantially, the most expensive component, the PV panel, has to be considered. If the PV size decreases to 5 watts, the sale price of the system will meet the specification.

TABLE 1: ESTIMATED TOTAL PRICE OF LANTERN SYSTEM WITH 8 WATT KONARKA'S DYE-SENSITIZED SOLAR MODULE

Lantern component	Retail price	Estimated capital cost (whole sale price)
5-watt CFL (works with DC lighting)	$24	$12
8-watt Konarka's dye-sensitized solar modules	N/A	$20 ($2.5*/peak watt)
7.2-Ah VRLA battery	$20	$10
Charge controller	$25	$12
Housing	N/A	$10
Total capital cost of the system		$64
Market cost (with an additional 30%)		**$84**

*Input from Konarka Technologies

TABLE 2: LANTERN COMPARISON OF THE FOUR COMMERCIAL LANTERS AND THE NEW DESIGN WITH THE PRICE OF $74 (USING 5 WATT PV MODULE AT $2.50 PER W)

Lantern	1	2	3	4	New
Lighting Level (footcandles) measured 3 feet away from the source	1.68	2.91	1.69	0.34	3.88
Hours of Operation (h) with fully-charge batteries	5.4	6.9	3.6	6.6	17.0
Price ($) Including Solar Panel	70	70	149	209	74
Mass (lbs)	2.0	3.0	2.0	2.5	8.5
Ratio of Effectiveness (fc-h / $-lbs)	**0.065**	**0.096**	**0.020**	**0.004**	**0.105**

From Table 2, lighting level, operating hours, price and the ratio of effectiveness are compared among the four existing commercial lanterns and the new design. The ratio of effectiveness is defined by lighting level multiplied by usage hours and divided by price times weight (fc-h / $-lbs). The lantern with the higher number in this ratio performs better to fit the design specifications. The comparison shows that if the system uses a 5 watt instead of 8 watt module, the ratio of effectiveness of the new design is the highest. Even though the daily usage time of the new design is less than 5 hours, the $74 price and the large storage (up to two days) will compensate this draw back.

4. MERGING TECHNOLOGIES: LED LIGHTS, ULTRACAPACITORS AND DYE-SENSITIZED PV MODULES

4.1 Ultracapacitor

As a new type of high energy storage, a low internal resistance capacitor, called a supercapacitor, also referred to as ultracapacitor and Electrochemical Double Layer Capacitor (EDLC), is thought to be excellent replacement for batteries in many applications requiring a higher power draw. The most common capacitors for electrical circuits store energy in the thin layer of dielectric material supported by metal plates (electrodes) acting as the terminals for the capacitor. Energy stored in a capacitor in the form of separated electrical charge depends on the area of the electrodes immersed in an electrolyte and the distance of the separated charges.

The greater the area and distance, the greater the capacitance. The electrodes for an ultracapacitor are fabricated from a porous carbon-based material having pores of diameter in the nanometer range. The charge separation distance is determined by the size of the ions in the electrolyte. The separation distance is much smaller than with conventional dielectric materials.

The energy stored in a capacitor is given by $E = \frac{1}{2}*C*V^2$, where C is its capacitance (Farads) and V is the voltage between the terminal plates. This means that the capacitor energy increases by the square of the voltage applied. The charging and discharging of a battery depends on chemical reaction. The energy can only be delivered at a low rate with low power in conventional capacitors. The energy stored in an ultracapacitor can be delivered almost instantly and does not depend on chemical reactions. The ultracapacitor cycle life is much longer and can be up to 100,000 charge/discharge cycles.

Testing of ten ultracapacitors of 10 Farads at 2.5 V (costing $100) indicates that one LED white bulb can meet the reading task requirement for 1.25 hours.

4.2 LED

The recent design of clustered light emitting diodes (LEDs) have extraordinary bright light, draw astonishingly little power (not for area lighting but for task lighting for reading, for example), and are extremely long-lived (average 100,000 hours). Even the higher cost of LEDs can be compensated for by the low energy consumption which means using with smaller and less costly PV panels, and the duration of lifetime. For task lighting, lamps in 3500 to

4000 degree Kelvin range are recommended (8). The higher concentration of ultraviolet found in the full spectrum and halogen lamps should be avoided for task lighting. LED lights are the most energy efficient for reading tasks on a small area (but at 20-25 lm/W not for area lighting). One LED bulb was found adequate to use for reading, and the color temperature is close to sunlight, i.e., 5500K color temperature, white, with 1500 milli-candelas, 40 degrees viewing angle, 3.4/4.0 typical/maximum voltage, 0.12 watt power consumption, -30 to +80 °C operating temperature, and cost $1.85.

4.3 Dye-Sensitized PV Module

If the new technologies are developed in the near future, the low cost dye-sensitized solar modules would be used to charge the lanterns with CFL lights for area lighting and then eventually the ultracapacitors powering the efficient LED headlamps for task lighting in small areas. The ultracapacitors would need no controller for charge and discharge, increasing reliability and reducing life-cycle costs.

5. SUMMARY

There are no consistent criteria among countries as to the "right" level of light for a specific task even within a given country over time. Recently recommended illuminance levels in several countries tend to converge at levels significantly lower than those existing in recent decades. For the new design, the Netherlands Energy Research Foundation (ECN) standards are used both for area lighting 25 lux (2.5 footcandles) and reading task lighting 50 lux (5 footcandles).

Advantages of the new design include adequate illuminance of 25 lux at 1 m (3 feet) away from the light source, meeting the ECN standard for area lighting, high color rendering index (CRI = 81) and properly correlated color temperature (4100 K), large battery storage (up to 15 to 17 hours when battery is fully charged), 360° light around the lantern, with a removable slide-in aluminum reflector, 5 W CFL, replaceable with a higher rated power (7, 9, 11, or 13 watts), with a weight of less than 4 kg.

6. REFERENCES

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[1] Netherlands Energy Research Foundation

[2] A steradian is defined as the solid angle which, having its vertex at the center of the sphere, cuts off a spherical surface area equal to the square of the radius of the sphere. For example, a one steradian section of a one meter radius sphere subtends a spherical surface area of one square meter.

[3] The solid angle that the base of the lamp blocks some light

[4] Energy Sector Management Assistance Programme, World Bank