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Development of Low Cost Solar Illumination System for Household

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Abstract: Solar electrification to serve certain appliances, which consume less power, is highly desired and less expensive to afford in a household. The use of fewer solar panels can further reduce the cost of procuring the equipment. The main objectives of the present study were to establish the minimum numbers of cells that can illuminate a household based on certain energy requirements and the identification of best lighting appliances to maximize the energy usage. In order to achieve these objectives, experiments with various arrangements of panels, (n) all linked to a common battery storage and dc to ac inverter, were carried out and different lighting appliances, which include ordinary white, fluorescent and Light Emitting Diode (LED) bulbs, were used. It was found that to obtain optimum voltage-current output, a series-parallel arrangement, with the n series connection giving higher voltages and the series connection giving higher amperes, yields the best result. It was also established that LED bulbs consume less power. The payback period for LED bulbs operating on the system was also found to be the best for the system.

Key words: Solar illumination, photovoltaic panel arrangement, efficacy

INTRODUCTION

Today, there is nothing that impinges on the cost of living and in the course of its uses degrades the environment more than energy use. The limited supply of today main energy sources (oil, coal, uranium) with the attendant hazard will force us-sooner or later -to replace most of the currently used power supply with *renewable* energy sources, the mostly likely, which is solar energy that neither get exhausted nor have any significant harmful effects on our environment. Unless we can soon develop low cost technologies for solar energy, which is within the reach of the people rather than somewhat higher conversion efficiencies-the demand will remain very low.

Fuel-based (especially kerosene) lighting presents significant health and environmental hazards over electrical lighting. There are thousands of household fires per year caused to fuel based lighting claiming thousands of lives (Zhou and Narendran, 2005; McNelis *et al*., 1988). Particulates from the fuel lanterns coat walls and lungs with carcinogenic residues. Although lighting systems powered by photovoltaic PV panels have existed for many years, they are not widely used, especially in lighting buildings, due to their high initial cost and low conversion efficiency (Zhou and Narendran, 2005; McNelis *et al*., 1988; Posnansky and Gnos, 1994). In rural areas and at remote locations solar electricity is an energy source, which can be a good alternative to other energy sources.

There are basically two distinct parts to the home lighting system using PV panels. The first is the number of panels involved and the type of lighting appliances used. The second is the technical challenges facing PV-powered lighting systems and how to use the dc power generated by the PV module to energize common light sources that are designed to operate efficiently under ac or dc power. Usually, the efficacy of dc light sources is very poor compared to ac light sources. Rapid developments in light emitting diode, LED and incorporation of dc to ac inverter have made this technology a potential candidate for PV-powered lighting systems (Zhou and Narendran, 2005; Davidson and Komp, 2000; Derrick *et al*., 1989)

Unfortunately, as with PV systems, many of the superior characteristics of LEDs are not appropriately evaluated in traditional economic analysis. A mix of measures should be considered. Comparisons of LEDs to compact fluorescent lamps are made usually on the basis of lumens per watt and the cost of the light source. Additional metrics that should be used for PV LEDs in a developing world context should include general usefulness, system life, efficiency, power requirements, total energy consumption, hardware costs and overall life cycle costs.

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In the past, inadequate system design and sizing of PV system components have led to unfavourable experiences (Hynes *et al*., 1995). However, in recent years PV energy systems have proved to be reliable if sufficient attention is paid to the design. The energy supply of PV lighting system has to be determined and because of the high investment costs of PV panels and the storage batteries, it is important to consider how to limit the number of these equipment used in any system of application, to identify appliances, which consumes the least energy and to ascertain the payback period of the whole system. These are the objectives of the study presented here.

MATERIALS AND METHODS

The basic experimental unit consisted initially of 5 PV panels (2), which were connected one to the other either in series or parallel or a combination of these to form a module, as shown in Fig. 1. A typical module used in this study produced 45 V at 2 amp under temperature and sunlight conditions of 32°C and 1.401kW m^{-2}; on cloudy days, this was less. The number of solar panels used depended on energy requirement and the amount of sunlight in the same period. Since, no electrical power was required or necessary to overcome cloudy days and to overcome the night period, some form of energy storage was incorporated. Several types of storage batteries were available; but a 24V Nickel-Cadmium (NiCd) or dry battery (3) was considered to be most suitable for this set up. The operation of the batteries required much attention during the experimentation with the PV-system. The discharge was not allowed to be less than 30% of the total capacity or to be overcharged using a controller. From a technical point of view deeper discharge was possible, but the lifetime of the battery then decreased dramatically and when overcharged has a bad influence on the performance of the battery. Moreover the total capacity of the battery then declined. Lighting appliances used were a compact fluorescent, CF (7), linear fluorescent, CL (8), 3 ordinary white (9) and 5 white Light Emitting Diodes (LEDs) (10) bulbs. Other components included a potentiometer (5), dc to ac inverter (6), dc to ac and dc switch over control (4) and a photo sensor (optional), which was used to measure the luminosity of the appliances.

A laboratory room size of 3×4 m^2 was lit by the appliances in turn. The PV panels were hung at the rooftop and tilted at 17^0. The PV-system was arranged and scaled to the electricity demand. A single module provided enough energy to light the apartment; this arrangement ensured that a number of modules could provide enough energy for an entire household. A new system could begin with one or two modules for the most urgent purposes. The system arrangement also ensured that expansion was possible when more applications were envisaged, or demand grows or when additional funds become available. When the expansion did take place, the composition of the whole system, modules and storage and power conditioning, were taken into consideration, in order to maintain an optimal performance.

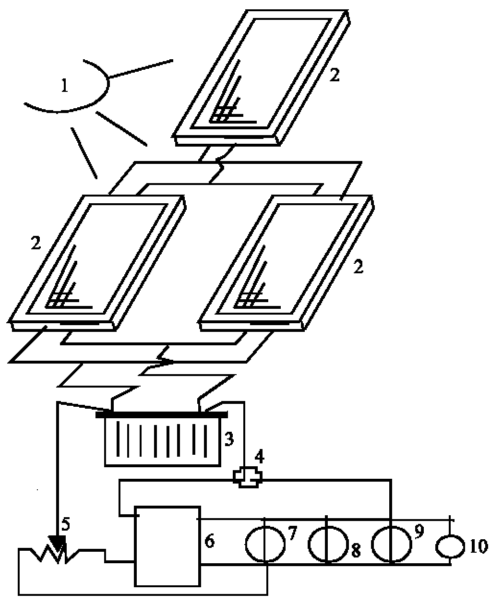

Fig. 1: Schematic of the experimental setup

The most important aspect was the amount of sunlight since the irradiation varies during the year and was also dependent on the orientation of the unit, latitude, the weather (climate) and geographical features of a location. It was in this circumstance that the unit was orientated to face north-south direction for maximum collection. The device was placed in the sun around noon and temperature measurements were taken with a digital thermometer every fifteen minutes for eight hours a day for 20 working days. The room was kept dark with black curtain.

The battery was charged with the solar panels. The experiment was then performed using stored energy from the battery to light the different appliances. A potentiometer connected ensured that the right voltage and current are supplied to the appliances.

Another feature considered in this set up was the use of dc to ac inverter and switch-over control so appliances like the ordinary white bulb, CF and LF tubes can be tested.

Finally, energy payback time, EPBT, which is the energy analog to financial payback, defined as the time necessary for a photovoltaic panel to generate the energy equivalent to that used to buy it was calculated as given by Alsema *et al.* (1998) and Knapp and Jester (2000) as:

$$\text{EPBT}=\frac{\text{Specific Energy}}{\text{Generation Rate}} \quad (1)$$

The system efficacy, E for the system in lighting applications, expressed as lumens per watt of solar energy that arrived at the PV panels, was calculated as follow:

$$E=\eta_{pv} \text{ x } \eta_{b} \text{ x } \eta_{dc\text{-}ac} \text{ x } \eta_{lm} \text{ [lm/W} \quad (2)$$

Where,

η_{pv} = PV panel efficiency; assumed.
= 18%
η_{b} = Battery efficiency; assumed.
= 80%
$\eta_{dc\text{-}ac}$ = Power-conditioning unit efficiency; based on the experiment.
= 87%
η_{lm} = Efficacy of light source lm/W.

The luminaire efficiency, η_{lum} was obtained as follow:

$$\eta_{lum} = \frac{A_{output}}{\sum A_{lumens}} \quad (3)$$

Where,

A_{lumens} = Appliance total output lumens.
Σa_{lumens} = Total lumens from appliance.

The process energy was derived from actual utility bills and monthly production data from November through December, 2007, the period within the experiment took place, using the existing consumption tariff.

RESULTS AND DISCUSSION

The experiment started with the five panels. However, it was discovered that to obtain the output voltage of 24 V and 5 A requires a series-parallel arrangement with just a maximum number of 3 panels, one in series with two others placed parallel. Unless higher output voltage and current were required, adding more panels was unnecessary. This number was examined theoretically, using circuit theory and the arrangement was found to reduce the number of panels used.

The lumens per watt of each appliance, (with LED = 25lm/W, CF = 40lm/W, LF = 85lm/W and WB = 65lm/W) were then calculated, using that of LED as an example and was given by Eq. (1):

Table 1: Lumen/watt of appliances

Appliances	η_{pv}	η_{th}	η_{b}	Lm/W	
LED	0.18	0.8	0.87	25	3.13
WB	0.18	0.8	0.87	40	5.01
CF	0.18	0.8	0.87	65	8.14
LF	0.18	0.8	0.87	85	10.64

Table 2: Luminosity per unit power for appliances

	LED	Ordinary white bulb	CF Bulb	LF Bulb
dc to ac inverter PV+battery	✔	✔	✔	--
lm/W	3.13	5.01	8.14	10.64
Luminate efficiency	83%	60%	80%	71%
EPBT	15years	8years	10years	12years

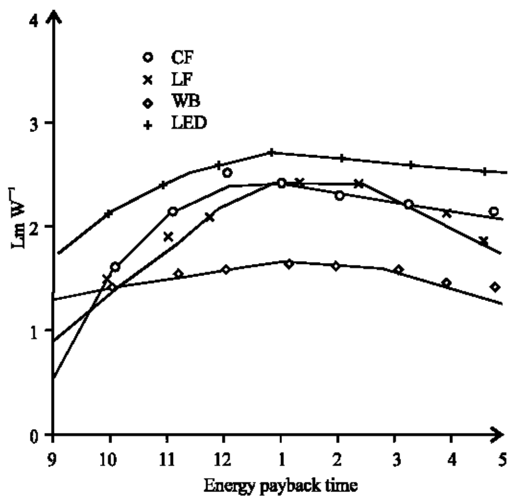

Fig. 2: Appliance lumen per watt over a period of time

$$E=\frac{18\times 80\times 87}{100\times 100\times 100}\times \text{ 25 lm/W}$$

$$= 3.132\text{lm/W}$$

The values for other appliances were similarly calculated and presented in Table 1.

Table 2 consisted of the appliances various efficiencies, given by Eq. (2) and payback time, given by equation by Eq. (3) as well as whether the appliance required inverter or not.

Subsequently, the average behaviour in terms of lumens/Watt of the appliances for the 20 days, from 9 a.m. in the morning to 5 p.m. in the evening was obtained and plotted in Fig. 2.

Finally, the energy payback time was assessed using Eq. (2) over the 20 days period vis-à-vis the utility bill over the same period and the results obtained extrapolated over a period of time graphically. The results are depicted in Fig. 3.

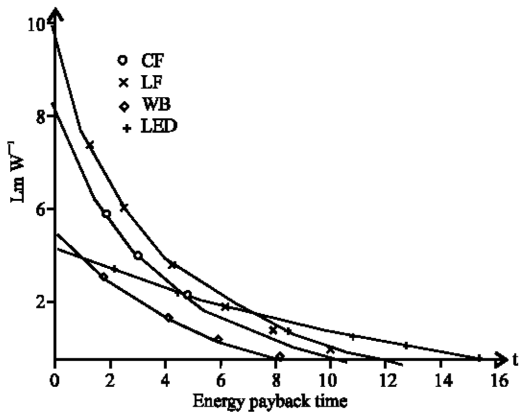

Fig. 3: Appliance lumen per Watt over a period of time

Usually, the efficacy of dc lighting is very poor compared to ac lighting as can be seen in Fig. 2 and this is even very much less than the lumens/watt calculated for each appliance.

With the PV-powered lighting system, it was observed that every 45V of PV panels coupled with 10 white LED bulbs can replace a bulb 3m fluorescent luminaire under the ideal solar condition.

For instance, a 3 45V of PV panels outside the building will convert enough solar energy to produce 3600 lm in a 12 m^2 room with white LED bulbs with a utility-connected PV- powered lighting system under the ideal solar condition of light output are about equivalent to the light output of a recessed fluorescent luminaire using two bulbs in each luminaire.

The EPBT of present PV systems is quite high, which could be as a result application of the system in a relatively high sun radiation environment. The results in Fig. 3 indicate that payback times for the photovoltaic panel lighting are substantially less than their expected lifetimes. With a module lifetime of 15 years, the panels analyzed here will produce five to eight times the energy from national power supply and dc-ac ten times, a measure referred to as the "energy return factor" in some of the relevant literatures (Zhou and Narendran, 2005; Posnansky and Gnos, 1994).

The effects of the other components of a photovoltaic system can be significant relative to the module payoff itself, most notably because a battery is used and the system also consisted of dc-ac inverter and potentiometer. Including life-cycle energy balances, BOS in both module used and BOS design are necessary to claim sustainability.

Estimated cost of electricity obtained from the photovoltaic panels ranges from 23-33 naira/kWh, but is expected to go as low as 2.2-2.4 naira/kWh, where one hundred and seventeen naira equals a dollar.

Construction work to install overhead or buried power cables is completely eliminated. These lights can be installed in a single day and turned on immediately after installation. As an added benefit, because the lighting fixture generates its own electrical power, it will continue to operate even during power interruptions or power failures resulting from natural disasters.

CONCLUSION

Using solar power to generate electricity for lighting and low power consumption LEDs help keep running costs down. Even though the white LED bulbs are not yet the most efficacious light source for PV-powered general illumination in buildings, their advantages should not be underestimated. A PV-powered LED lighting system has higher energy pay back time and reduced maintenance costs because of the LED bulbs' longer life. Also, LED bulbs can fit into smaller, flexible lighting fixtures, making them useful for lighting tight spaces. Photovoltaic (PV) coupled with Light Emitting Diodes (LEDs) offer a more practical, economic and better energy and lighting alternative to other lighting appliances.

The PV module has no moving parts, therefore repair is almost never needed and the maintenance requirements are moderate, when well designed a system operates very reliably.

However, there are challenges as well to designing for LED lighting system. In order to optimize the size of a PV module, the battery energy should be stored and used as efficiently as possible, for example, when using a 24 Volt battery to power a 3V, 50 mA LED, the current flow must also be regulated for a LED, with a high degree of reliability since the effective LED operating currents are on the order of 20 - 350 mA.

Nomenclature:

η_b : Battery efficiency.
$\eta_{dc\text{-}ac}$: Power-conditioning unit.
η_{lm} : Efficacy of light source lm/W.
η_{pv} : PV panel efficiency.
ac : Alternating current.
A_{lumens} : Appliance total output lumens.
Σa_{lumen} : Total lumens from appliance.
CF : Compact fluorescent.
dc : Direct current.
E : System efficacy.
EPBT : Energy payback time.
LED : Light emitting diode.
LF : Linear fluorescent.
lm : Lumen.
PV : Photovoltaic.

T : Time.
V : Voltage.
W : Watt.
WB : White bulb.

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