A Rapid, Low-cost Testing Procedure for Measuring Light Output of Portable Lanterns with Results for Five Rechargeable LED Lantern Models

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Abstract

The welcome entrance of rechargeable devices in communities with no access to grid electricity brings with it goods of varying quality. Quick and easy product testing can help inform field staff and end-users in which models to invest time and money. This paper lays out an inexpensive procedure for quantitive comparison of lanterns and reports results for a group of five rechargeable LED lanterns.

1. Introduction

Off-grid households in developing countries have an urgent and largely unmet need for household electricity services, particularly lighting, mobile phone charging, and power for small appliances such as radios. As recently as 2009 the rural electrification rate in sub-Saharan Africa was only 14.3%, and remains below 10% in many countries in the region. [1] Those without grid access generally rely on expensive and inefficient substitutes, such as dry cell batteries, kerosene wick lamps and candles, which have low upfront costs but higher long-term expenses. [2]

Although new technologies such as solar rechargeable LED lanterns are more efficient and cost-effective in the long run, rural consumers may perceive them as risky investments due to higher upfront costs and lack of information regarding quality. Consumer exposure to low-quality devices can lead to market spoiling and reduced trust in the worth and reliability of broad classes of new products which may hinder similar products from gaining acceptance and market penetration. [3] Because the value of a rechargeable lantern with high initial costs may only become evident over longer term use, it may be difficult for consumers to decide among a range of lighting products with a wide variation in quality, features, and form factors. A lack of independent testing, quality assurance practices and official regulation only adds to this problem.

As lantern manufacturers and development programs continue to introduce lanterns into new markets, a basic set of tests to evaluate lantern performance and quality is advantageous not only to the customer, but also to the industry overall. Our goal is to demonstrate a relatively simple, inexpensive and rapid test that can be applied in field settings to support recommendations of lanterns available for purchase in rural Africa. This approach is proposed as an alternative to more detailed light testing techniques which produce more precise results but typically require relatively expensive equipment (such as photometric spheres), highly skilled testers and time-intensive procedures that are beyond the means of many laboratories or programs active in rural, developing country settings.

While established techniques exist to measure isotropic (point source) and Lambertian light, the lights tested for this study do not fit neatly into either category. [4] Our approach, adapted from an earlier in-house method, collects data on lantern light output using a low-cost lux meter in a darkened room. Overall lantern performance is evaluated by calculating total light output and efficiency which are reported in two main metrics: lumen-hours and luminous efficacy. The data obtained enables direct comparison to traditional fuel-based lighting options, as well as incandescent bulbs and compact fluorescent lamps (CFLs). This comparison emphasizes the potential value offered by higher-efficiency LED lighting systems, particularly for communities currently dependent on batteries or fuel for light.

2. Procedure

The basic procedure for evaluating lanterns began with reviewing lantern features and specifications. Lantern models were then catalogued and put through light testing, which consisted of two main parts: a temporal test which measured light discharge from a lantern starting with a fully charged battery until off[1], and a spatial test which measured light intensity values at different locations from a fully charged lantern. Next, metrics such as lumen-hours, luminous efficacy, and cost per lumen-hour were calculated, and, finally, results were compared to other light sources commonly used in developing countries.

2.1. Lantern Selection and Features

Five major lantern models designed for use in rural settings in developing countries were selected for testing. This study focused on a subset of lanterns available on international markets (though not necessarily in African village or urban markets) at a wholesale price below $50 which had the following features: an LED light source; a rechargeable built-in battery; and with an individual solar panel available for off-grid charging. They also were expected to produce sufficient light to be used for either task lighting or room lighting (i.e., testing did not include solar 'torch' models). Within these parameters, lanterns

[1]see section 3.1 for discussion of designated 'off' point

chosen for testing covered a range of sizes and form factors, battery types and capacities, and other design characteristics. All lanterns offered at least two light-level settings, and some had one very low setting sometimes referred to by manufacturers as a "nightlight" or ''bed light," intended for families with very young or breast-feeding children. Most basic features can be ascertained from product specification sheets and quick visual assessment. Table 1, below, presents the basic features of the 5 models tested, with each lantern assigned to one of two broad categories – task or room light – depending on the lantern's form factor as well as the dimensions and brightness of the light cone, which are the strongest indication of a lantern's intended purpose. Lantern brand and model names have been omitted from this paper.

	TASK 1	TASK 2	ROOM A	ROOM B	ROOM C
Estimated Retail Price:	∼$20	∼$20	∼$35	∼$40	∼$60-70
Light Source:	1 LED	4 LEDs	1 LED	1 LED	1 LED
LED Lumen Rating:	not provided	2000-3000 mcd ∼6.3-9.4 lumens	not provided	not provided	90-100 lumen
Number of Light Level Settings:	2	4	3	4	3
Hours of Light By Setting: HIGH, MED, LOW (bed light or night light marked with *)	4, 15	10, –, 36, *	3, 5, 10	6, 10, 20, *	4, 10, 200
Includes Mobile Phone Charging?	No	No	Optional	Yes	Yes
Battery Chemistry:	NiCd	NiMH	NiMH	SLA (VRLA)	SLA (gel VRL
Battery Rated Capacity (Amp-hours):	400 mAh	1300 mAh	2100 mAh	1300 mAh	4500 mAh
Battery Rated Capacity (Watt-hours):	1.44 Wh	1.56 Wh	15.12 Wh	7.8 Wh	27 Wh
Battery Rated Voltage:	3.6v (3x 1.2v)	1.2 v	7.2v (6x 1.2v)	6.0 v	6.0 v
Solar Panel Peak Wattage:	0.627 W	1.0 W	2.5 W	1.3 W	2.0 W

Table 1: Basic Features of Lanterns, By Model (Information from product specification sheets or visual inspection). *"Bed light" or "night light" levels were not tested due to the difficulty of measuring very low lux levels over long durations.

2.2. Equipment and Experimental Setup

Three lanterns of each model were purchased and tested, and results were averaged for each set of three, with the following exceptions: only two 'TASK 2' lanterns were tested and averaged, and only one pre-production lantern of the 'ROOM C' model was available at the time of testing. Before testing, leads were attached to the batteries in the lanterns and extended through small holes drilled in the lantern casings to permit rapid and frequent voltage readings during charging and before and after light testing.

Testing and analysis required the following:
(Note that many items can be replaced by similar or generic tools for the same functionality.)

- dark room: a windowless room with minimally-reflective walls and floor (for more detail see discussion of error under section 5.1) and enough floor space to measure at least 2 meters in one radial direction;
- handheld lux meter: Extech 401036, measuring 0.01 to 20,000 lux with a 3 digit readout, accurate to +/- 3%;

- measuring tape or ruler: at least 2 meters, in cm;
- post or stand: at least 1.5m tall with fasteners, clamps, or similar, to hang lanterns above floor;
- digital multi-meter: Fluke 8010A, measuring DC voltage from 100μV to 1000 V, accurate to +/- 1%;
- Microsoft Excel: used for recording data, calculating results and charting light readings; best-fit function was used for data curve-fitting;
- Python (optional): for data calculation with numpy and scipy and plotting with matplotlib;

2.3. Methodology for Light Testing and Data Analysis

For each light test, a lantern was suspended above the floor in a darkened room, switched on to a specific light setting, and the light levels were measured with a lux meter placed on the floor. This initiatory configuration set up testing for spatial and temporal components of light output:

1. Temporal tests measured center-beam lux at several time points throughout a full battery discharge for each light lantern power setting.
    - Each lantern was charged using a DC power supply set to voltage and current ratings given in the lantern's documentation or inferred from accessories (solar panels, AC/DC charger adapters). For those lanterns with charge-control circuitry, charging was automatically stopped by the lantern itself. For those without, charging was stopped manually when the battery voltage leveled off. Battery voltage was measured and recorded at the point of 'full charge'.
    - In the testing room: The fully-charged lantern was suspended from a point either 50 or 100cm from the floor facing down. The default height was 100 cm, but low-power lanterns, such as the smaller desktop models, which gave an initial center-beam reading below 25 lux at floor level were lowered to 50cm to allow for more lux readings within the meter's accuracy range.
    - Two lux meters were placed directly below the suspended lantern: one on the floor and one halfway between the floor and the lantern, taking care to make sure that one lux meter did not shade the other. Thus, for a lantern suspended at 100 cm height, the meters were 50 and 100 cm away; for lower power lanterns suspended at 50 cm height the distances were 50 and 25 cm. (Note that all models had at least one set of readings at a common distance (50 cm) for comparison.)
    - The room was darkened, the lantern was activated to whichever setting was to be evaluated, and automatic lux readings were initiated and logged automatically every 10 minutes until lantern was fully discharged. Each light-level setting was tested separately, in this same manner, except for the 'bed light' settings for which light levels were typically too low for the lux meter to produce reliable readings.

- When the lantern automatically switched off or was emitting light levels well below the designated end of discharge cycle (50% of initial lux), the test was stopped, and data logged by the meters was transferred to a computer.
- The final battery terminal voltage for the lantern was measured and recorded.

2. For spatial tests, multiple lux (lumens/m^2) readings were taken along one radial line of the light cone just after a fully-charged lantern was switched on. These data were used for calculation of total lumen output at a single time point.
    - The lantern was fully charged (as per temporal testing)
    - The lantern battery's starting voltage was recorded.
    - In the testing room: The fully-charged lantern was suspended from a point 100 (or 50cm) from the floor facing down (as per temporal testing).
    - A lux meter was placed directly underneath lantern in the center of the light beam.
    - The room was darkened, and the lantern was switched on to the setting to be evaluated.
    - The lux value at center-beam was recorded, followed by additional lux measurements at 5 cm increments moving horizontally outward along the radial line, until the measured lux value fell below 10%[2] of center-beam value.
    - The lantern was lowered to half the previous height (to 50cm or 25cm) and the same pattern of measurement was repeated.

Spatial data (total lumens) and temporal data (hours per discharge) multiplied together provide a rough estimate of lumen-hours per discharge, a common metric that can be used for direct comparison of lanterns with different design features from different manufacturers. The primary factors that affect lantern performance include the power level and efficiency of the LED and circuitry, the housing, lens, and screen surrounding the LED, and the battery chemistry and capacity. More detail on these tests is given below.

3. Testing

3.1. Temporal Tests

An important metric for consumer evaluation of a lantern is the number of hours of light it can provide from a single charge. This is among the first questions asked by purchasers and is often printed on a product's box or listed

[2] see section 5.1 for explanation of 10% point

on the manufacturer's specification sheet or website. Performance in this area varies widely among lantern models. Many lanterns, particularly less expensive models available in rural markets in developing countries, provide bright light only for a short period, showing dramatic drop-off in lux levels soon after being switched on. This can make it difficult for consumers to assess lights at the point of purchase, since viewing a lantern's light output only briefly at full charge may give a misleading impression of overall performance. For this reason, both the average light level and the consistency of brightness throughout a discharge cycle are important measures that can help quantify a lantern's utility.

Temporal testing for this study sought to verify manufacturers' claims by timing how long it took for a fully-charged lantern to discharge. A lux meter was positioned at the point of maximum light output (typically the center of the light cone, or 'on-axis') and lux values were recorded automatically at 10 minute intervals using the lux meter's datalogging function for the duration of a full discharge cycle. These lux values, plotted against time, created discharge curves specific to each model and light setting. Many lantern models, particularly higher-priced models with multiple light settings, include discharge control circuitry that maintains a nearly constant voltage and light level during discharge. Others include discharge control called a 'low-voltage disconnect' which shuts off the light completely when a set voltage point is passed. Some lanterns produce light levels that drop steadily as the battery discharged. For those that had tapering light levels, a complete discharge was designated as the point when center-beam lux measurements fell to half (50%) of the initial value. This cutoff point was chosen both because light strength typically dropped very quickly after the 50% point, and also because it is assumed that light levels below 50% would offer substantially less utility for owners, particularly when using lights for work.

3.1.1. Temporal Data

Temporal light measurement data (lux vs. time) was graphed in Python to create 'discharge curves,' (see Figure 1) showing how light levels change over time. In this figure, discharge curves for 3 'room' lanterns are displayed in red and labeled with letters A-C; curves for 2 'task' lights are displayed in blue and labeled with numbers 1 and 2. The lantern setting, medium, is indicated in parentheses. Differences in the maximum height and total length of discharge curves tend to reflect differences in LEDs used and the total capacity of the lantern's battery relative to the light's power consumption. The differences in the shape of the discharge curves – particularly the steepness at the end of the discharge curve – typically reflect the variations in battery chemistry and circuitry among the lantern models. To compare two examples: 1) The gradual downward slope at the end of the discharge curve for the 'TASK 1' lantern reflect the NiCd battery without discharge control circuitry. In contrast, the square shape of the 'ROOM B' and ROOM C' lanterns (which shows an abrupt fall in light levels at the end of the curve for all settings), arises from the lanterns' lead-acid batteries and charge/discharge control circuitry producing a consistent light level followed by sharp shutoff. In this study, 'room' lanterns typically exhibited discharge control while 'task' lanterns did not, as seen by the square vs. slowly tapering curves for each type, respectively. Each of these factors is important for overall light performance: stability vs. gradual decline in light levels affect usability; discharge control is a means of protecting batteries, and lack of this circuitry may lead to frequent or severe deep discharge, leading to reduced overall battery life.

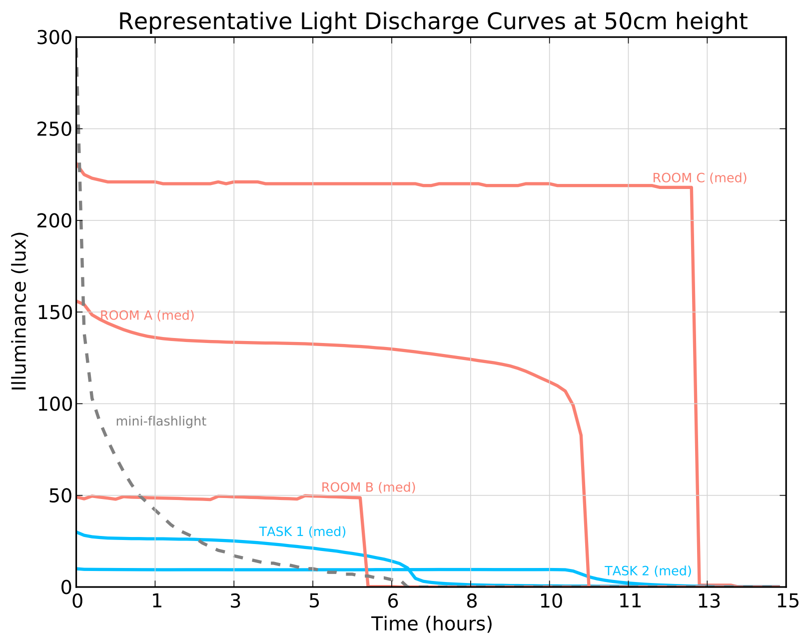

Figure 1: Lux vs. Time Discharge Curves for 3 'room' lights (letters) and two 'task' lights (numbers) on medium setting, plus one 'mini-flashlight' at its only setting.
Note: Each curve is a single representation of a one lantern's discharge cycle on 'medium', not an average of multiple tests. 'TASK Light 1' has no 'high' setting for models offered outside India.

The ROOM B and C lanterns both display a rectangular discharge profile, indicating that light output is relatively consistent over the entire discharge period until the light is abruptly shut off. For these lanterns, a lux measurement taken from almost any time point during discharge represents fairly accurately the lumen output throughout the entire discharge at a given setting. Thus, for these lights, simple multiplication of the total duration of discharge with the total lumen output at the start time (see following section on spatial data) gives a rapid and quite accurate computation of lumen-hours. The other lantern discharge curves (TASK 1, 2, and ROOM A) show significant deviation from this rectangular shape, with decreasing light levels in some or all of the discharge profile, and so would require a more detailed approach to calculation.

This difference in the shape of lantern discharge profiles – the consistency of light output throughout the discharge cycle – is an important aspect of lantern usability and perceived quality. It is common among inexpensive LED lanterns, particularly those powered by disposable dry-cell batteries, to show very steep drop-off in light output in the initial minutes of use. This is illustrated by inclusion in Figure 1 of a discharge curve for a disposable 'mini flashlight' which displays almost a negative exponential decay in light output. This device was an inexpensive keychain light with no internal circuitry to control current to the LEDs. As can be seen from its discharge curve, the bright light emitted in the initial moments of discharge is not sustained. A brief, visual assessment of a new light of this model by a potential purchaser would be a poor indication of its performance over time, potentially leading to customer disappointment and market spoiling. In contrast, some lanterns may have circuitry to intentionally produce anomalies in light output toward the end of a discharge cycle, such as blinking or falling light levels, to warn users of the need for recharging and thus prevent user disappointment at a sudden shutoff.

To provide some quantitative insight into the issue of light consistency, we propose one metric which roughly indicates the relative variation in light level across lantern models during discharge: the standard deviation from average lux during a discharge half-cycle as a percentage of the average lux. Figure 2, shows results for the lanterns tested, at each setting. The mini-flashlight – essentially a set of 4 LEDs powered by 3 button batteries in a plastic casing – could not be added to this plot because its light strength dropped very quickly, declining well beyond the 50% level before the second lux measurements. For an idea of how inconsistent its light output was: there was no point (due to the light strength's steep decline) where the light leveled out until the very end, when light levels were well below 50% of initial lux, and where light consistency, in this definition, would be negative.

A perfectly flat discharge curve would have a constant lux equal to the initial lux, and thus a 100% value for the inverse standard deviation as a percentage of average lux (our chosen metric). The ROOM B and C lights have nearly this profile, with very straight discharge curves (∼1% standard deviation, around 99% light consistency). This can be explained by the fact that both use lead-acid batteries, which already have a relatively flat discharge profile, as well as additional discharge control circuitry with an abrupt shutoff when the battery terminal voltage falls to a specified level. All the other models show some gradual decline in light strength throughout the discharge half-cycle, with or without a final cut-off point, and thus result in lower values for this same metric (down to 85%).

This metric adds quantitative clarity to points mentioned above within the discussion of Figure 1. The first is that, for lanterns with flat discharge profiles, a fairly accurate calculation of total lumen hours can be obtained from the product of the the duration of discharge in hours, from the temporal tests, with the total lumen output at a single time point (obtained using the spatial test, described below). However, for lanterns with greater variation in light output during discharge, a calculation of total lumen-hours will be inaccurate if based

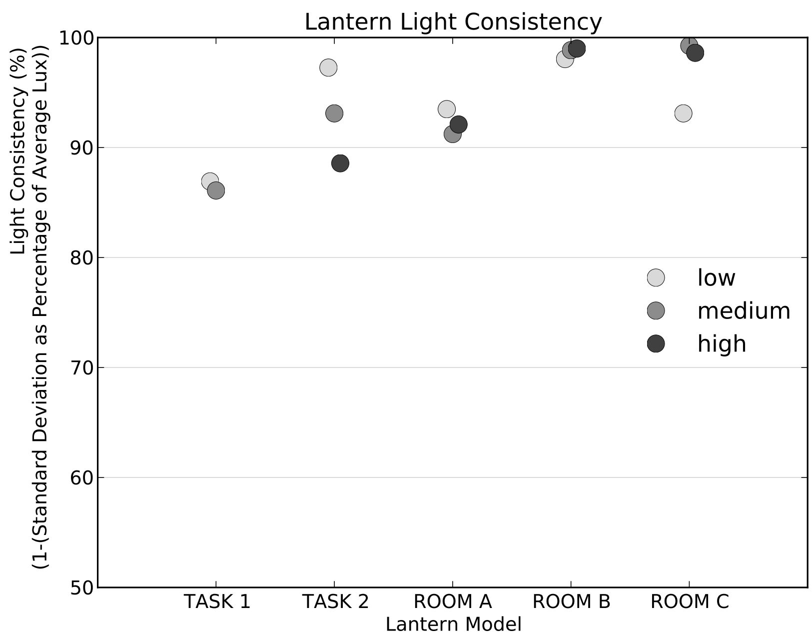

Figure 2: Lantern Light consistency for the 5 lanterns tested, at each light setting. Light consistency is defined as 1 minus light inconsistency, which is proposed to be the standard deviation of lux (during light discharge until the lux falls to half the initial lux) as a percentage of average lux.

upon lux measurements taken from any single time-point during discharge. For example, measurements for the TASK 1 light, set to medium, vary by up to 15% from the average value. For these lanterns, assessment of the average lumens during discharge is more complex. Each center-beam lux reading in a temporal discharge curve corresponds to a total lumen output for the entire light cone at that moment. A Riemann sum of all the normalized lumen outputs per time interval provides a more accurate estimation of the total luminal output (in lumen-hours) of the discharge cycle.

3.2. Spatial Tests

Both the total light emitted at a given time point and the spread of the light over a given area are of concern to rural villagers, who may need ambient (room) lighting for activities such as dining and socializing, or more focused (task) lighting for indoor or nighttime work. Lantern designs tend to fall into one of these broad categories (or a third, 'torches' not tested here), though some designs include lenses, reflectors, or other features that modify light spread in an attempt to offer some combination of these lighting services in a single unit.

Unlike temporal metrics such as 'hours of light,' which are reasonably clear to consumers, the overall brightness and spatial spread of a lantern's light output are less easily described in ways that can be easily conveyed to consumers. A simple method to allow comparison of total light output can help lantern users and purchasers to evaluate lantern options for different needs.

Our approach to spatial testing measures illuminance (incident light, in lux) at points distributed over a lantern's lighted area at floor level. More accurate results for a lantern's light output can be obtained with use of expensive equipment (such as an integrating photometric sphere) or with more detailed testing protocols (some of which specify modifications to lanterns, such as removal of screens and coverings to expose the LED). Mikhail Dubinovskiy proposes a method using lux datapoints taken across the beam [5], while ANSI and the IEC publish an industry light measurement standard using an integrating sphere or goniophotometer. [6] In contrast, this study uses an inexpensive and simple approach which tests light output with a handheld lux meter and with the lanterns in their original condition (i.e., with screens/housing intact) to rapidly obtain results useful to field practitioners. This spatial lumen test relies only upon one radial line of lux measurements taken below the lantern which becomes a basis for describing light spread in all directions and calculating overall brightness in units of total lumen output.

3.2.1. Spatial Data

For a visual understanding of light distribution for each lantern, curves of lux versus horizontal distance from centerbeam are displayed in Figure 3. The region of the light cone near the central axis represents the main beam of the light, and extends to the point where the lux value falls to around 50% of the center-beam lux (indicated in the plots of Figure 3 by a vertical line). The tail-ends of the curves in this chart, where light strength tapers to 10% (also known as the field radius) of its center-beam value, are indicated by second vertical lines. The spread of a lantern's cone of light is a characteristic of the lantern itself, resulting from the LED and housing (including the screen, lens, or reflector), and is independent of overall brightness of a lantern or specific setting. In fact, the curves for the 'task' lights appear flatter, while the curves for at least one of the 'room' lights show steeper fall-off in light levels with changing radius, indicating greater focus of the light cone for that room light than for the task lights. This suggests that, to the first approximation, the key difference between room and task lights is one of overall brightness, rather than the shape of the light cone. Our results suggest that the light cone of task lights is not much more focused, on average, than room lights; however, task lights are typically lower-powered, and have added design features, such as bendable necks which allow closer placement of the light, and more precise aiming of light for detail work in a smaller lit area.

These lux versus radius curves can then serve as a basis for computing total light output for each lantern and setting, during one full battery discharge. Since lumens is simply lux per square meter, integrating each lux curve from centerbeam to the field radius and rotating 360°around the central axis gives

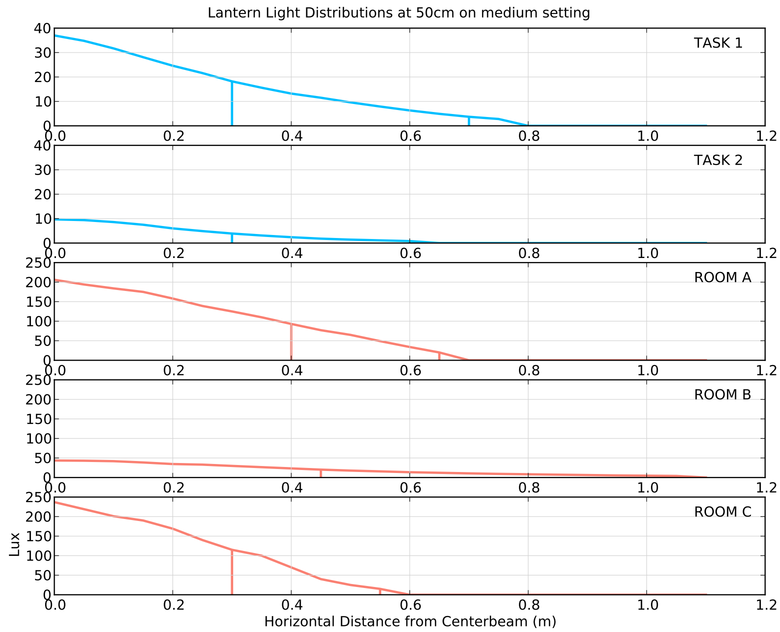

Figure 3: Light Distributions of all lanterns on medium setting at 50cm height. Vertical lines represent beam radius and field radius, respectively. Note that task lanterns' y axes go from 0-40 lux, while room lanterns range from 0-250 lux, for relative comparison within categories.

an approximation of the total lumens emitted. One option might be to utilize Excel's 'best-fit' function to obtain an equation, f(r), for each curve, integrate this function to find the area beneath it, and then rotate from 0 to 2π around the vertical axis to create a solid representing the full measured light output at a given time point. This double integration can be performed by treating this volume as an infinite number of infinitely thin shells of radius r, height f(r), and thus $area = 2\pi r f(r)$, according to the following formula:

$$TotalLightOutput = V = 2\pi \int_0^R r f(r) dr \tag{1}$$

where the outermost limit of integration, R, is defined as the outer radius of the light cone, i.e., where lux fell to 10% of on-axis value. Simple numerical integration of the spatial lux data proper (without first converting to a function) works in the same manner; for instance, this paper uses simple ring integration (summing the products of the lux values with the area of the corresponding rings of lighted floor).

4. Results and Analysis

4.1. Lumens, Lumen-hours, and Luminous Efficacy

Results of the integrations for total light output (in lumens) are presented in the first three rows of Table 2, for different lantern models and settings. Depending on the light setting, the desktop models (TASK 1 & 2) provided approximately 1 to 18 lumens (computed from measurements of roughly 5 to 25 lux at 50cm height), while the room lanterns (A, B, & C) averaged 3 to 130 lumens (from measurements of 25 to 350 lux at 50cm height). In comparison, a 60-watt grid-connected incandescent bulb typically provides around 800 lumens [7], though it is important to note that the LEDs tested here tended to be powered at a level on the order of roughly one watt, and LEDs are generally a few times more efficient than incandescent (depending upon the precise type and quality of each). Referring back to Table 1, manufacturers' lumen ratings were available only for TASK 2 and ROOM C lanterns, and in both cases the results obtained by our testing method agree roughly with the manufacturer's specification (approximately 10 and 130 lumens vs. 9 and 100 lumens, respectively).

	TASK 1	TASK 2	ROOM A	ROOM B	ROOM C
Lumens - High:	—	10.41	123.55	72.78	136.51
Lumens - Med:	18.01	4.04	101.05	50.13	83.59
Lumens - Low:	4.95	1.92	46.59	26.46	2.42
Lumen-hours - High:	—	49.02	572.7	322.7	963.8
Lumen-hours - Med:	78.22	45.18	722.1	397.7	1009
Lumen-hours - Low:	78.20	50.32	621.9	488.8	388.4
Luminous Efficacy(lm/w) - High:	—	27.89	54.43	70.66	40.99
Luminous Efficacy(lm/w) - Med:	52.98	23.77	58.07	78.33	38.17
Luminous Efficacy(lm/w) - Low:	49.51	21.31	57.52	82.68	18.89

Table 2: Total lumens, lumen-hours, and luminous efficacy for multiple lanterns and settings.

Subsequent rows in Table 2 include results for computation of two standard metrics to evaluate and compare lanterns: lumen-hours, and luminous efficacy. Rows 4 to 6 provide results for different lanterns and settings for lumen-hours, a measure of total light output per charge which is calculated by a second integration, i.e. summing each time interval's weighted total lumens value (obtained by normalizing the lux data obtained during the temporal test against the on-axis lux value of the spatial test which produced a specific lumen output). In other words, looking back at the discharge curves in Figure 1, each point during discharge reflects a specific luminal output, that, due to falling light levels, must be recalculated for each time interval, based on the lumens produced at time zero during a separate spatial test. The lumen-hours value is affected most by battery capacity and LED power level; thus smaller, less expensive lanterns (such as task lights) tend to rate lower. The task lanterns afforded 50-80 lumen-hours per battery charge, while the room lanterns gave off 300-1000 lumen-hours per charge. While lanterns cannot easily be compared to grid-connected lamps, light from traditional, fuel-based lights, such as a candle or small kerosene wick lamp, emits approximately 8-10 lumens for 3-5 hours which computes to 25 - 50 lumen-hours in a day's typical use before the candle or additional kerosene must be repurchased. This leads to costs of between US$40-60 per year for these fuel-based technologies, versus estimates of less than US$5 per year (including equipment and operating costs) for a solar-powered LED. [7]

Rows 7 to 9 provide results for a third metric, luminous efficacy, a technical measure of lantern efficiency, calculated by dividing total lumen output for each fully-charged lantern by that lantern's measured electricity consumption. In the lab this was measured simply by measuring the voltage and current across the fully-charged battery when the lantern was turned on at each light setting. The lumens calculated from the spatial test divided by power consumption (in watts) gives luminous efficiency (in lm/W). This value is typically determined by the efficiency of the circuit and LED. The desktop lanterns used in this study ranged from 21 to 53 lm/watt efficiency, the room lanterns were roughly 20-80 lumens/watt, while reference values for the candle and kerosene wick lamp both lie below 0.2 lumens per watt. [7]

As can be seen from Table 2, both metrics vary independently among the models. A small desktop model, such as the TASK 1, may have high luminous efficacy despite low overall light output, and a strong light emitter, such as the ROOM C, may not be relatively efficient. It is also important to note that these metrics are intended only as broad technical indicators, to be included among other considerations in an overall assessment of quality or suitability for a given purpose, since there may not be a simple correspondence between a single metric and overall lantern quality. For example, lanterns with features such as 'low voltage disconnect' – which enhances battery life by preventing deep-discharge of the lantern battery thus potentially increasing overall value – may nonetheless show lower overall lumen-hours per charge.

Figure 4, compares luminous efficacy data obtained in this study with reference values for several widely available lighting technologies. Though this study conducted limited tests of a small number of lanterns, results are nonetheless roughly consistent with reference values showing LED lights to average around 3 times more efficient than a standard incandescent bulb and multiple times more efficient than traditional fuel-based lighting. This efficiency gap is expected to grow in the future, with projections in the range of 150 lumens per watt for white LEDs by 2015. [9]

4.2. Battery Capacity and Cycle-Life:

Battery type, capacity, and charge/discharge control are important factors in lantern performance, and relate closely to trade-offs such size, weight, price, and charging needs (particularly duration and cost of solar panels or other accessories). Key characteristics include capacity, in milliamp-hours (mAH) or watt-hours, which affects the total lumen-hours a lantern can provide per charge-discharge cycle. Battery cycle-life (the total number of cycles before performance drops and a battery needs replacing) is another important factor in a lantern's long-term value and perceived quality. Replacing batteries can be difficult and costly in rural areas with limited supply chains. [10] For this reason,

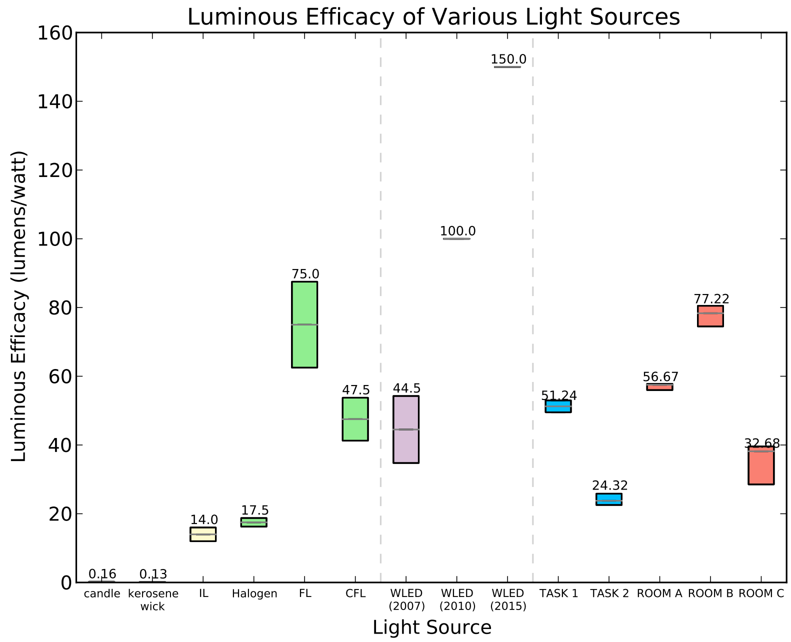

Figure 4: Luminous Efficacy among the 5 models tested, compared with various other lighting sources for comparison. 'IL' is incandescent light, 'FL' is (linear) fluorescent light, and 'CFL' refers to compact fluorescent lights. [8] [9]

protective circuitry – such as charge and discharge control to prevent overcharging, cell voltage-reversal (for nickel-based batteries) and deep discharge, all of which shorten battery life – is a particularly valuable feature of lantern design, though unfortunately this protective circuitry is not typically evident to consumers. Other factors – including choice of a battery for which there are supply chains to rural areas for replacement, strengthening existing battery supply chains, educating consumers, and branding of products – may be equally important considerations for LED lantern manufacturers and vendors. This is because a poorly performing battery can be indistinguishable to an end-user from a failure of the lantern overall. This is particularly problematic for LED lanterns, since the long life of LEDs themselves (thousands of hours, equivalent to years of use, allowing multiple battery replacements for single lantern) are a key aspect of an LED lantern's long-term value to the end-user relative to other lighting options, not only candles and kerosene, but also other lights with non-LED bulbs or disposable batteries.

Although this study did not measure specific factors in battery performance such as round-trip efficiency over the charge-discharge cycle, it is worthwhile to consider battery standards, based on chemistry, along with some data obtained from simple laboratory tests presented in Table 3.

	TASK 1	TASK 2	ROOM A	ROOM B	ROOM C
Battery Type:	NiCd	NiMH	NiMH	SLA (VRLA)	VRLA (gel)
Cycle Life: (standard)	1500	300-500	300-500	500	500
Charge Control:	YES	YES	NO	YES	YES
Discharge Control:	NO	NO	YES	YES	YES
Depth of Discharge*:	100%	100%	82%	67-80%	100%
Estimated Cycle Life:	<1500	<500	<500	>500	500

Table 3: Battery-related characteristics of all lanterns tested. *For those models with discharge control, Depth of Discharge was estimated by comparing the average measured final open circuit voltage of obtained from discharge tests with standard discharge curves for specific battery chemistries.

While all three room lights included discharge control, only ROOM B and C lanterns also showed relatively consistent light levels throughout discharge, yielding light discharge profiles (Figure 1) that are rectangular in shape. This 'flat' discharge curve suggests that a quick calculation can be used to confirm the depth of discharge values reported in Table 3 which were obtained by comparing measured open circuit voltages on battery terminals at the end of discharge with standard depth of discharge charts. Assuming that light intensity is an indicator of power consumption, then for a lantern with consistent light output, total energy consumed during discharge is simply the product of the duration of discharge multiplied by the measured power consumption in watts. Then, a comparison of energy consumed (Wh) versus the total battery capacity (Wh) gives depth of discharge for each lantern and light setting. Though imprecise, and only available for two lanterns, results from this calculation correlated well with the estimates in Table 3. For example, the calculation yielded a value of 66% depth of discharge for ROOM B, and about 96% for ROOM C, versus 67-80% and 100%, respectively, in Table 3.

Circuitry to control both charge and discharge cycles of lantern use can impact battery life, an important factor in long-term value for the end-user. Our evidence indicates that only the ROOM A and B models have a low-voltage cut-off set to a level (80% D.O.D) that prevents frequent deep discharge with ordinary lantern use. The other lanterns (TASK 1, 2, and ROOM C) appear to discharge deeply (100%) if the light is left on indefinitely, which can adversely affect battery life for all types of batteries (chemistry) considered in this study. Observations while charging lanterns in the lab indicate that all, except the ROOM A lantern, exhibited some form of charge control to protect the battery from harmful over-charging. Considering the likely contribution of both charge- and discharge-controls, our tests can support very rough predictions for battery life, which are shown in the lowest row of Table 3. Overall, it can be expected that the relative lack of either charge or discharge control for four lantern models (TASK 1 and 2, and ROOM A and C) may provide short-term benefits such as more lumen-hours per discharge for lanterns without low-voltage disconnect features, but in the long run will show diminished long-term performance in the form of reduced battery life and longer required charging times, or both.

Figure 5, shows a close correspondence between total light output (in lumen-hours) versus battery capacity (in total nominal Wh). Data points of the lantern models were used to calculate the least squares regression line (dashed grey line), and those that fall below the line are the same models which showed lower luminous efficacy values (see values for TASK 2 and ROOM C lanterns in Figure 4).

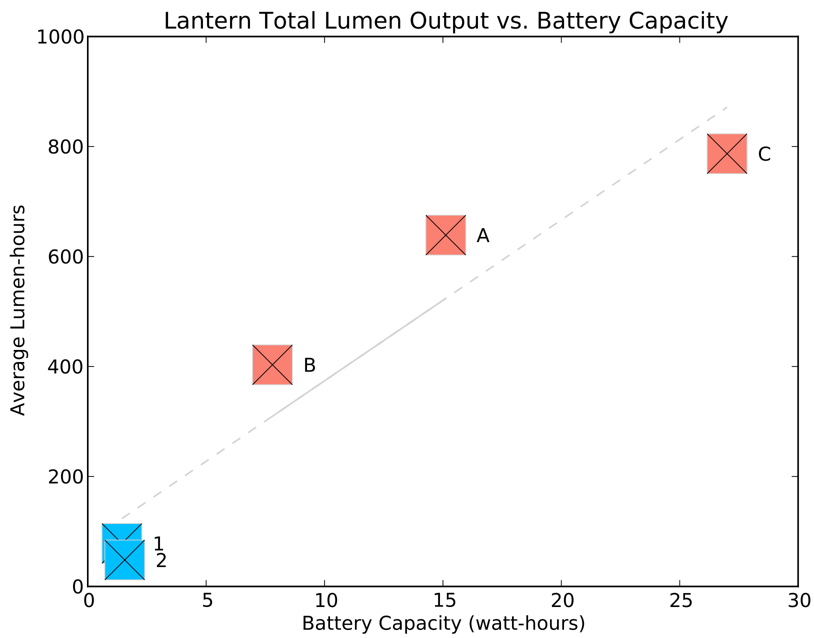

Figure 5: Lantern Models: Total Lumen Output* (during one discharge) vs. Battery Capacity. The dashed line is the least squares regression line for all lanterns tested and represents the average increase in lumen-hours per increase in battery capacity.

Multiple technical tradeoffs may need to be considered together in comparing overall lantern performance. For example, the Room C lantern has a battery approximately 3 times the total capacity of that of the Room B lantern, yet only approximately one-half the luminous efficacy (see Tables 1, 2). Simple arithmetic suggests then that the Room C light should produce around 50% more net lumen-hours per discharge than the Room B lamp. However, despite this lower efficiency, the Room C light provides three times the total lumen hours of the Room B light, and this appears to be achieved by deep discharge of the ROOM C lantern's battery (refer to Table 3). In fact, a sample production lantern sent afterwards by the manufacturer of the ROOM-C model showed dramatic self-discharge in the battery after a single discharge test, indicating that the deep-discharge typical in this model may damage the battery.

4.3. Cost per Light – Comparison among different lighting sources

Multiple technical and cost metrics can, in turn, be combined to create a common metric that goes beyond performance to express value. Given the estimated retail price of the lanterns (from Table 1), the light output in lumens for each lantern on 'high' (from Table 2), and the approximate battery cycle life for each lantern (Table 3), a comparative analysis of total cost of light per unit of service, in US$/1000 lumen-hours (as seen in Mills [7]) allows the lanterns in this study to be compared with each other and with other lighting sources. Assumptions made in the calculations included: a) lamp usage of 4 hours/day with one recharge per day, b) initial cost is amortized over 3 years, c) grid electricity price of US$0.10/kwh, d) AA NiMH battery life of 500 cycles, etc. Other assumptions were added to permit inclusion of lanterns in this study: a) the initial lantern price includes the lantern with the solar panel, b) replacement batteries would be available for roughly 10% of this initial package cost, b) the TASK1 lantern battery would last 1500 cycles, while the TASK2, ROOM A, B, and C would last for 500 cycles (Table 3). Calculations were carried through only for the highest setting available on each lantern. In the following plot (Figure 6), the lanterns from this paper, particularly the 'ROOM' lanterns, perform on par with other solar lanterns with rechargeable batteries provided in the literature (the solar 5W CFL and solar 1W LED [7]). When available, grid-connected light (incandescent and CFL) cost substantially less to use, while the pressurized and hurricane kerosene lamps cost per unit service is comparable to the LED lanterns tested in this study. Other factors, such as CO2 emissions (24-391 kg/yr) associated with kerosene, and potential health risks can add arguments for transition away from fuel-based lighting. [7] [11] Meanwhile, our results support the conclusion that, by using fuel-based lights with low up-front costs, the poorest are paying more in the long-run.

5. Discussion

Lantern performance and light output can be summarized by two main metrics, total lumen-hours per charge and luminous efficacy, which together give a good overall understanding of relative lantern performance and a means to compare different models with a wide range of specifications and features. A measure of light consistency is an additional useful and relevant aspect of lantern operation to consider. Although the models in this study provided fairly stable light strength throughout a discharge half-cycle, light drop-offs were detectable, and can potentially be quite dramatic (as seen with the mini-flashlight). Likewise, battery capacity, cycle-life, and charge control influence long-term lantern performance and therefore are important in lantern evaluation.

5.1. Sources of Error

Whereas established techniques for gathering data and calculating these two standard metrics can be detailed and complex, this study sought to establish

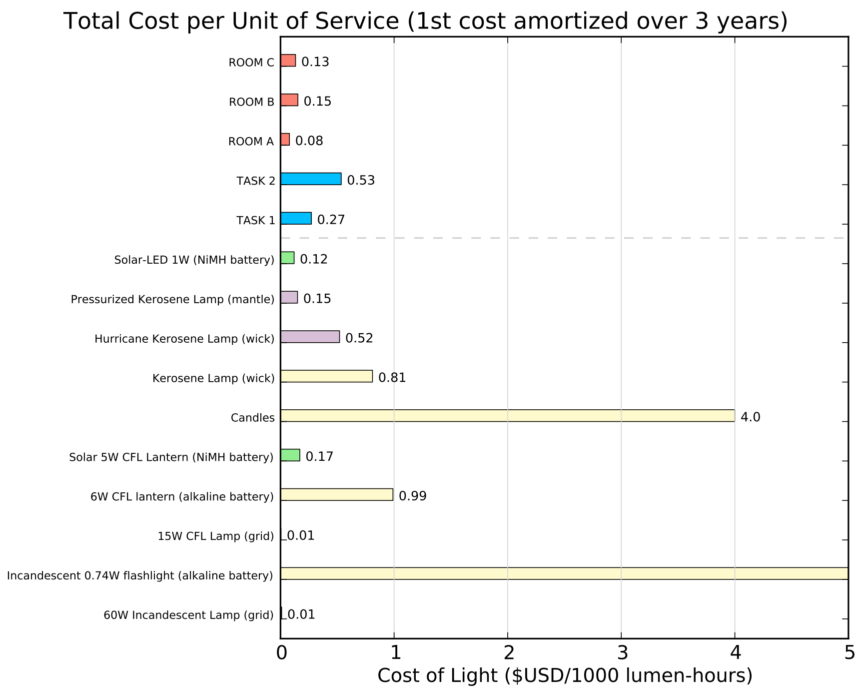

Figure 6: Total Cost of light per unit service for various lighting sources [7]. The incandescent flashlight costs $38.02/klm-hr, but was cut off from the graph in order to make all light sources' data clearly visible.

a simple, rapid, and inexpensive means of assessing lantern performance. Accordingly, this approach required some assumptions and introduced some error. Assumptions for the spatial testing method and total lumen output computation outlined above include: a) that the lantern can be approximated as a point source, and thus forms a radially symmetric light cone; and b) that measurement to the radial distance where lux values fall to 10% of the center-beam value constitutes sufficient coverage of the entire lit surface. The first assumption is seen as acceptable since all lanterns in this study contained LEDs within a mostly symmetrical reflective housing and lens which acted to even out directional light.

The second assumption stems from the industry standard of using 10% of on-axis luminous emittance as the end-point of the reach of irradiance and is supported by the observation that, past that point, lux values tended to level off, indicating lux meter increased response to reflected light or ambient light. Particularly for lanterns set at low light levels, lux measurements beyond 10% of the center-beam value often fell into a range that was poorly measured by the light meter. Thus, this methodology may engender error in the range of perhaps 5-10% which is likely to be unavoidable in practice. Other sources of potential error are estimated as follows:

- human error from tilting the lux meter, variations in light output during testing, internal batteries at slightly different states of charge before testing, etc. These are sources of relatively small error that are difficult to quantify; however, averaging data across three tests presumably diminishes their effect to negligible levels.

- precision and accuracy of the lux meter: $\sim \pm$ 3% (specification from lux meter manufacturer)

- error from ambient light reflection (floor, walls): $\sim$ 5-6%. To test the extent of this error, light readings were taken with the meter shielded from the direct light beam and compared with unshielded readings, and the difference was a maximum of 6%.

- error from lumen-hour calculation: $\sim \pm$ 5% . This error stems from the procedure of sampling lux data at 5cm increments and varies depending on light spread (determined by lantern model and height during testing).

Since this research was meant to measure lantern light performance quickly and inexpensively, final lumen results are mere approximations to the actual light output. Various factors may introduce errors, and there exists no direct data to check, absolutely, the accuracy of the lumen calculations. However, the range of lumen outputs and luminous efficiency values fit within the values seen by standard LEDs on the current market. Additionally, the manufacturers of two of the lanterns (TASK 2 and ROOM C) offered specs on the lumens emitted by their LED. These values were reasonably close to the values calculated through this research (see section 4.1 on lumens, lumen-hours and luminous efficiency).

Although it would be impossible to further check lumen accuracy without the same expensive equipment for which this research is attempting to serve as an alternate, data precision was validated by observing that, over several tests and units, lumen data clearly converged, for each model at a specific light setting, to an average value (see Table 2). This implies that, although the overall method of lumen calculation may introduce indefinite error, relative error among the lanterns utilizing the same methodology is low, and, at the very least, lanterns can be evaluated in respect to one another. The same held true for the luminous efficiency calculations, which produced single values for each lantern (regardless of setting) that allowed direct comparison among models and later, estimated differences among various types of lighting systems. Overall it would be safe to conclude that lumens calculated through this methodology may incorporate absolute error of up to 20%, while relative error may be only 5-10%. For this reason the procedure and methodology outlined in this paper is most useful for quick comparisons across lantern models by fieldworkers or low-tech labs.

5.2. Potential Improvements

The fact that measured values converge helps validate our method of measuring and calculating these two figures; however, this research was a work in progress, and a few questions arose that suggested even simpler ways to collect the same data and improve accuracy. For instance, adapting the whole lux-measuring process to a spherical basis (rather than cylindrical coordinates) would further facilitate and streamline subsequent spread and total lumen calculations as well as provide real polar plots of lantern light emission, similar to the technique used by expensive equipment. Additionally, coupling the two tests, temporal and spatial, into one comprehensive and simultaneous measurement of data would eliminate any inconsistencies between the lumens emitted during different testing sessions when the battery may be at a slightly different state of charge. In essence, the spatial test would be carried out by rotating the lantern on a turntable while noting lux values from 0 to the 10% lux point (in degrees), which results in a polar radiation plot, while the temporal test is achieved by then leaving the light on to measure on-axis lux (at 0° rotation) automatically with the datalogger. This would be a simpler, cleaner, and faster method that would largely eliminate a few sources of error. Once the testing area is set up, lanterns (since relatively stationary) could be easily hooked up to a DMM to measure voltages (and even current, possibly, for power consumption data) concurrently. Whether a 'cylindrical' method, as used in this study, or a 'spherical' one (logging lux per angle with a turntable) is used, attempts to gather spatial, temporal, and power consumption data simultaneously would serve to streamline the procedure and reduce error significantly. Other factors, such as light screen symmetry, light quality (such as color and glare), and temperature tests might also be incorporated into the testing to further analyze lantern performance.

6. Conclusion

This research has proved to be useful and effective in providing technical recommendations of lantern models to field staff for market trials. In most cases, it has closely correlated with qualitative data obtained on-site in the field and market, which is remarkable considering the myriad of characteristics, such as form-factor and manufacturer staying power, not included in this analysis. For instance, recent field research in Bonsaaso (Ghana), Ikaram, and Pampaida (Nigeria) shows that, given a choice of lantern models similar to the group of lanterns used in this study, villagers consistently selected the lanterns with mobile phone-charging capability and a lead-acid battery. Mobile phone use, as a primary means of communication, has become so important that the phone charging feature often eclipsed villagers' interest in illumination. Furthermore, the preference for lanterns with a lead-acid battery stems from equating physical weight with quality and durability. For these simple reasons, the ROOM B and C models were easily the most popular among villagers, in spite of their higher purchase price.

Along these lines, the information obtained and methods developed by this research can be used in conjunction with qualitative data from the field to direct development projects towards quality LED lanterns that will endure market testing and actual use on-site. Future projects and manufacturer product introductions can utilize the quick and simple testing procedure outlined in this paper to zero in on lantern models which will be preferred by villagers and prove to be good long-term investments. In this way, inferior products can be avoided – a win-win situation for the manufacturers and distributors of quality lanterns and the rural customer alike. Pairing this technical information with field data provides direction for future product development as well, and as this type of research and general knowledge becomes more available, good quality lanterns can quickly enter the market with less chance of market spoiling from low-quality products. Further research in other lantern technical features such as mobile phone charging and battery charging, particularly with solar panels, is needed and would help to complete technical lantern assessments.

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