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Technical Report #4

Measured Off-Grid LED Lighting System Performance

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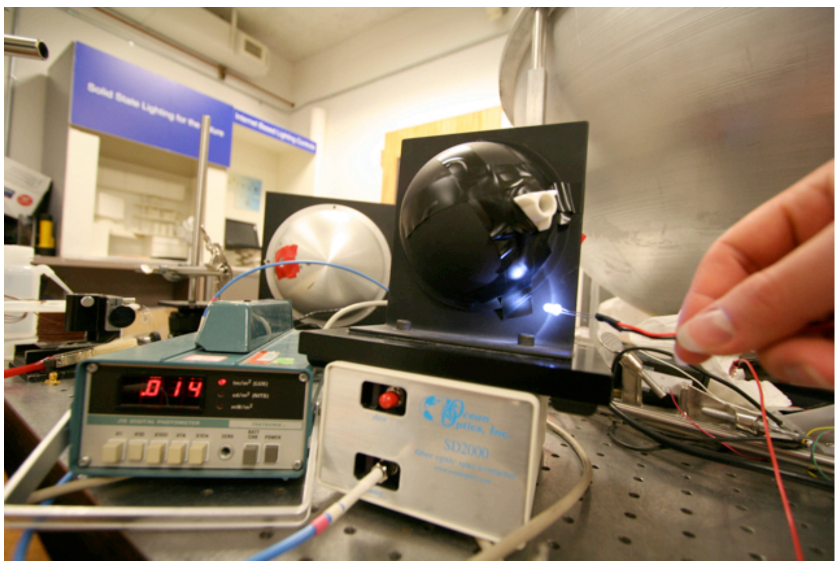

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The Lumina Project includes an Off-Grid Lighting Technology Assessment activity to provide manufacturers, re-sellers, program managers, and policymakers with information to help ensure the delivery of products that maximize consumer acceptance and the market success of off-grid lighting solutions for the developing world. Periodic *Research Notes* present new results in a timely fashion between the issuance of more formal and lengthy reports. Our results should not be construed as product endorsements by the authors. For a full archive of *Research Notes* and *Technical Reports* see: http://light.lbl.gov/technology-assessment.html

Motivation & Findings

The considerable energy use, cost, and greenhouse-gas emissions associated with fuel-based lighting,[1] in combination with increasing awareness of demand for improved lighting services in off-grid areas of developing countries, have given rise to a proliferation of new products based on LED light sources. While this rapid expansion provides a promising opportunity to increase access to electric lighting for low-income people, the quality of LED lighting products remains a concern. At present, reliable information about the performance of available products is in short supply. For example, there is currently no formal product testing or labeling process, and so consumers and even manufacturers often do not know how their products perform or compare to others in the market. At the same time, potential buyers of these products are highly price sensitive, which can create a tension between quality and affordability.[2]

This report is a product of our ongoing effort to support the development of high-quality yet affordable products that have good potential to succeed in the market. The effort includes work to develop low-cost testing procedures, to identify useful performance metrics, and to facilitate the development of industry standards and product rating protocols.

Our previous work has established that counterproductive "market spoiling" can occur if consumers are disappointed with the quality of these products or the level of services they provide.[3] We have also evaluated the efficiencies and energy losses associated with various components of off-grid LED lighting systems (e.g. light sources), and found a wide range of quality and performance problems.[4] This report extends that work by adding several new component tests and by quantifying the overall system performance for integrated products.

We conducted laboratory testing of nine distinct product lines. In some cases we also tested multiple generations of a single product line and/or operating modes for a product. The results are summarized in Table 1. We found that power consumption and light output varied by nearly a factor of 12, with efficacy varying by a factor of more than six. Of particular note, overall luminous efficacy varied from 8.2 to 53.1 lumens per watt. Color quality indices varied materially, especially for correlated color temperature. Maximum illuminance, beam candlepower, and luminance varied by 8x, 32x, and 61x respectively, suggesting considerable differences among products in terms of service levels and visual comfort. Glare varied by 1.4x, and was above acceptable thresholds in most cases. Optical losses play a role in overall performance, varying by a factor of 3.2 and ranging as high as 24%. These findings collectively indicate considerable potential for improved product design.

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[1] Mills, E. 2005. "The Specter of Fuel-Based Lighting," *Science* 308:1263-1264.
[2] Radecsky, K, P. Johnstone, A. Jacobson, and E. Mills. 2008. "Solid-State Lighting on a Shoestring Budget: The Economics of Off-Grid Lighting for Small Businesses in Kenya." Lumina Project Technical Report #3.
[3] Mills, E. and A. Jacobson. 2007. "The Off-Grid Lighting Market in Western Kenya: LED Alternatives and Consumer Preferences in a Millennium Development Village." Lumina Project Technical Report #2.
[4] Mills, E. 2003. "Technical and Economic Performance Analysis of Kerosene Lamps and Alternative Approaches to Illumination in Developing Countries." Lawrence Berkeley National Laboratory. Mills, E. and A. Jacobson. 2007. "The Need for Independent Quality and Performance Testing for Emerging Off-grid White-LED Illumination Systems for Developing Countries." Lumina Project Technical Report #1. Also published in *Light & Engineering*, 16(2):5-24.

Table 1: Summary of performance metrics and ranges

Performance Metric	Observed min	Observed max	Max/Min
Power (Watts)	0.13	1.51	11.6
Light output (lumens)	3.3	38.1	11.5
Luminous efficacy (lumens/watt)	8.2	53.1	6.5
Correlated color temperature (K)	8,528	31,069	3.6
Color rendering index	80.2	91.0	1.1
Maximum illuminance	24	200	8.3
Maximum beam candlepower	7.6	244.0	32.1
Luminance (cd/m2)	12,399	758,712	61.2
Daylight glare index (direct view)	23	32	1.4
Optical losses (%)	7.6	24.0	3.2

To maintain the anonymity of specific manufacturers, we have adopted a coded identification system that is similar to that used in prior reports. The code numbers that we use to refer to the off-grid product lines in this report are listed in the first column of Table 2. Where applicable, we list the code numbers that we used for these same products, in Lumina Technical Report #1 (see footnote 3) in the second column.

Table 2. Code Numbers for LED Products in the Report and Corresponding Code Numbers Used in Lumina Technical Report #1.

Product Code # (this report)	Previous Code # (Lumina TR#1)
1	25
2a	15
2b	15
3	n/a
4	24
5	n/a
6	n/a
7a	7
7b	7
8	n/a
9	17

Sample, Tests, and Experimental Setup

In the summer of 2008, we tested nine commercially available off-grid LED lighting systems to assess their luminous efficacy, color quality, luminous intensity, luminance, and glare. Note that the products chosen do not necessarily represent a cross-section of the entire market. Furthermore, in most cases, only one sample of each product was tested; we know from prior experience that performance varies even among nominally identical products from a given manufacturer. Moreover, most of these products are evolving as manufacturers learn more about performance and receive feedback from end users. For example, samples 2a and 2b represent two generations of a product from one manufacturer. The same is true for 7a and 7b.

For all tests, a regulated power supply was used in order to eliminate the influence of battery state of charge on the measurements. Each product was tested at a voltage and current, as defined by a set of specifications that were determined in previous bench tests with fully charged batteries. Color quality was characterized by the color rendering index (CRI), correlated color temperature (CCT), and x-y chromaticity coordinates. The equipment and instruments used during testing are described in Table 3.

In the sections that follow, we describe the procedures and results associated with each set of tests.

Table 3: Experimental instrumentation and equipment.

Description	Name	Accuracy	Notes
Power supply	TENMA 72-2075		Used in place of batteries
Power analyzer	Voltech PM3000A	+/-0.05% rdg, +/- 0.05% range	Off spec: 0.1% low on voltage, 0.75% high on current
Digital multimeter	Datron 1281	+/- 3 ppm, 150 ppm, voltage, current	Used to calibrate power analyzer
Oscilloscope	Tektronix 7623A	+/- 5%	
Integrating sphere		--	2 m
Integrating sphere	--	+/-3.1%	1m
Standard lamp	NBS calibrated 175W incandescent	--	Used w/ 2m sphere
Standard lamp	Labsphere calibrated quartz halogen	+/- 5% reflectance	Used w/ 1, sphere
Photometer	Tektronix J16, J6511 probe	+/-5%	Used with both spheres
Spot luminance meter	Minolta LS-110	+/- 2%	For luminance
Illuminance meter	Minolta xy-1 chroma meter	+/- 2%	For x-y
Rotary table	India	+/- ~0.5 degrees	
Illuminance meter	Minolta T-1	+/-2%	For candlepower
Spectrometer analysis software	NIST CQS_Simulation_7.1.xls		For quantifying correlated color temperature and color rendering index
Spectrometer	Ocean Optics SD2000, w/ OOIBase 32 software	+/- 0.01 for x & y coordinate values	For quantifying correlated color temperature and color rendering index
99% reflectance standard	Labsphere	+/- 1%	For manual x-y
Spot meter close-up lens	Minolta		For luminance
Neutral density filter	Tiffen ND1.0		For luminance

Luminous efficacy

Procedure

Luminous efficacy was measured using a 2m integrating sphere and photometer, a standard lamp, and power analyzer. The standard lamp was used to calibrate the measured results, accounting for the absorption attributable to each product's housing. The data collected during testing included: voltage, current, and lumens.

To begin each test, the effects of the light-source housing were quantified. The product-sphere system was calibrated by measuring the luminous flux of a standard lamp (2843 lumens) co-located in the sphere with the product in its 'off' state. Each product was then tested in its 'on' state (and with the standard lamp in its 'off' state). Data were collected approximately every ten minutes, over the period of an hour, to ensure the absence of time-dependent losses. Such losses were not, however, expected, as each product was tested using a power supply rather than a battery.

Procedural Exceptions

There were three exceptions to the procedure described above.

1) Products 1 and 8 did not operate at the specifications provided; a higher current was required to power the LEDs.

2) The power data from product 1 are of very low confidence. On the low setting the metered current was unstable. An oscilloscope showed a non-standard wave form, and that the product was drawing power in pulses. While the power meter samples at very high frequency, it is not likely that it is able to correctly process this peculiar waveform.

3). On the high setting, the metered current did not agree with that displayed on the power meter and there were no power specifications provided.

Results

Table 4 and Figure 1 summarize the results of the system-level luminous efficacy tests. We found that power consumption varied by a factor of 11.6 for the products tested, light output (lumens) varied by 11.5x, and efficacy by 6.5x. Product 5 showed the lowest efficacy. None of the products exhibited time dependent losses in efficacy.

Table 4: Luminous efficacy measurements.

Product	Power (W)	Lumens	Efficacy (lm/W)	Notes
Kerosene lantern[5]	0.01-0.035	8-40	0.08-0.11	
Incandescent GLS[6]	40-75	500-1200	12.5-16.0	
Compact Fluorescent Lamp (CFL)	5-24	220-1450	45-60	
1 – low setting	0.13	3.3	25.1	(b)
1 – high setting	.67	14.2	21.4	(c)
2a	0.35	13.6	39.2	
2b	0.36	12.8	35.8	
3	0.34	9.1	26.8	
4	0.43	13.9	32.7	
5	0.51	4.2	8.2	
6	1.26	16.7	13.3	
7a	0.74	38.1	51.4	
7b	0.35	18.5	53.1	
8	1.51	31.5	20.9	

(a) Current and voltage from the Voltech meter did not match those from the TENMA power supply, and the metered current was not stable. The power quoted is from the TENMA: 32mA, 4.1V.
(b) The Voltech and TENMA current measures did not agree. The power quoted is from the TENMA: 121mA, 5.5V.

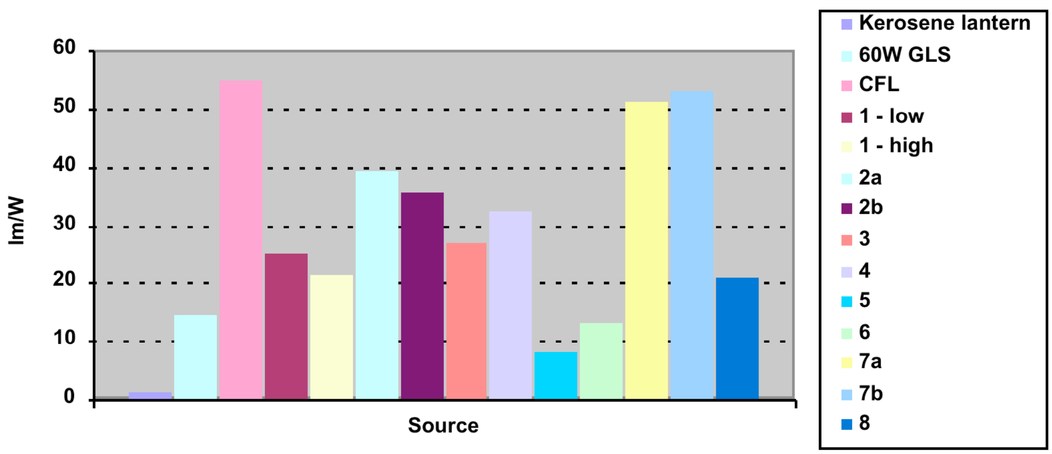

Figure 1: Distribution of luminous efficacy across 8 products tested, with kerosene lantern, GLS, and CFL references.

Color Quality - CRI, CCT, x-y Coordinates

Procedure

Color quality was measured using a 1m integrating sphere, a spectrometer, and a calibration lamp. The sphere was used to diffuse the light emitted by the product, so that directional effects were not present in the light sampled with the spectrometer. The large (2m) sphere used in the

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[5] Range reflects simple wick lamps and non-pressurized hurricane lanterns, from E. Mills. 2005. Footnote 3, Supporting Online Material, Table S3.
[6] GLS = General Lighting Source

luminous efficacy testing was too large relative to the size of the spectrometer's detector and the output from each light source, requiring use of a sphere with smaller dimensions (i.e., 1m instead of 2m). To account for the absorption attributable to each light source's housing and the sphere's paint, the product-sphere system was calibrated as in the luminous efficacy tests. NIST software (CQS_Simulation_7.1) was used to generate color quality measures from the spectrometer data and calibration results.

Results

Table 5 and Figures 2-3 summarize the results of the color quality tests. We found that CCT varied by a factor of 3.5 for the products tested and CRI by 1.1x. Product 1 had the highest CRI, while product 4 and product 7b were outliers with particularly high CCT (which is perceived as a relatively bluish light).

Table 5: CCT, x-y coordinates, and CRI.

Product	CCT (K)	x	y	CRI
Kerosene lantern	~2,000			
Incand. GLS	2,750			100
CFL	2,700-3,500			75-80
1	9,431	0.293	0.272	91
2a	10,165	0.279	0.287	85.2
2b	6,813	0.308	0.325	84.5
4	31,069	0.262	0.237	85.8
6	10,486	0.282	0.278	85.4
7a	8,528	0.291	0.298	82.2
7b	29,323	0.259	0.242	80.2
8	6,565	0.311	0.331	80.7

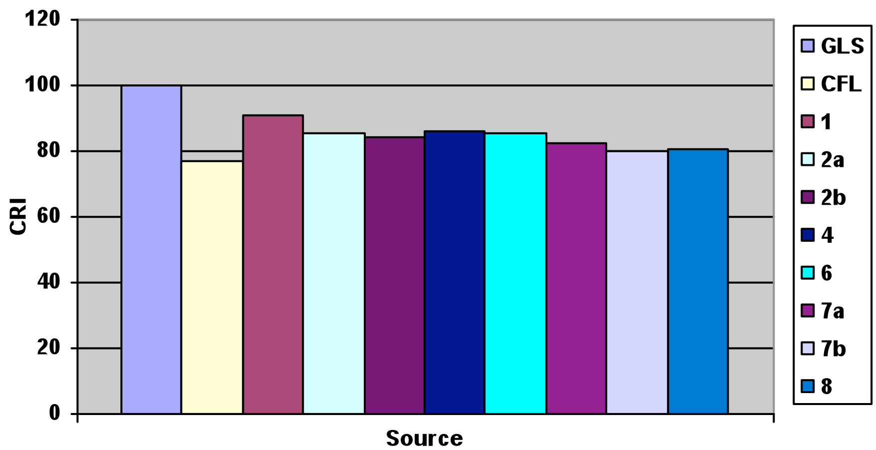

Figure 2: Distribution of CRI across 5 products tested, with GLS and CFL references.

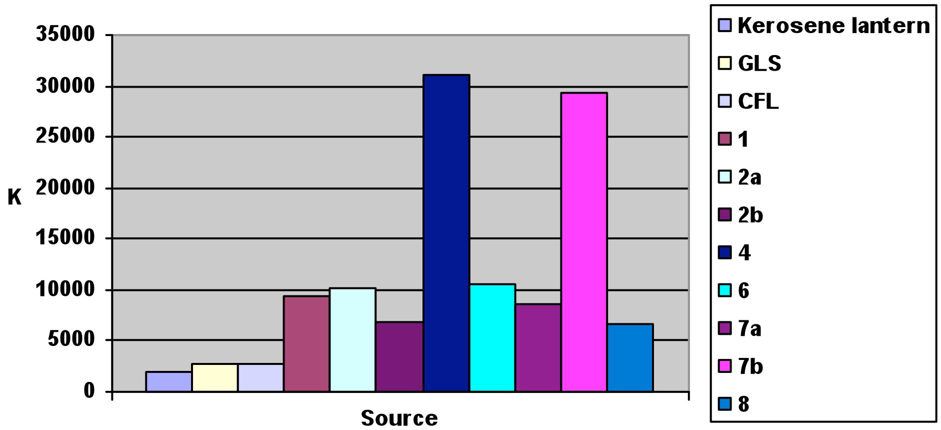

Figure 3: Distribution of CCT across 6 products tested, with kerosene lantern, GLS, and CFL references.

Illuminance, Maximum Beam Candlepower

Procedure

On-axis illuminance (lumens per square meter, lux) was measured using an illuminance meter. The meter was placed on a tabletop in a darkened room, and the product was suspended above it with a tripod. The position of the meter was adjusted perpendicular to the light source until the detected illuminance reached a maximum, and the illuminance (I) and distance from the meter to the light source (D) were recorded. The maximum beam candlepower MBCP was calculated according to the formula: $MBCP = D^2 \times I$.

Results

The results of the illuminance testing and candlepower calculations are provided in Table 6 and Figure 4. We found that maximum illuminance varied by a factor of 8.3 for the products tested, and maximum beam candlepower (MBCP) by 32.1x. Products should not necessarily be compared to one another, as the purposes of the products vary (e.g. some are for task lighting, others for way-finding, and others for ambient lighting). Product 4 was an outlier, with a calculated candlepower more than twice the magnitude of the next-highest performing product.

Table 6: Maximum beam candlepower and illuminance.

Product	Max. illuminance (lux)[7]	Distance to Light Source (m)[8]	MBCP (cd)	Notes
1 – high setting	1,410 (131)	0.24 (0.79)	82.1	
1 – low setting	386 (35.9)	0.22 (0.73)	19.1	
2a	1,485 (138)	0.22 (0.71)	69.2	
2b	1,109 (103)	0.24 (0.79)	64.6	
3				Damaged resistor
4	2,153 (200)	0.34 (1.1)	243.8	
5	750 (69.7)	0.22 (0.71)	35.0	
6	1,130 (105)	0.30 (0.98)	100.7	
7a	537 (49.9)	0.18 (0.58)	17.0	
7b	258 (24)	0.17 (0.56)	7.6	
8	264 (24.5)	0.21 (0.69)	11.6	
9	293 (27.2)	0.19 (0.63)	10.6	(a)

(a) Current and voltage from the Voltech meter did not match those from the TENMA power supply, and the metered current was not stable. The TENMA indicated that the light source was powered at 5.7V, 110 mA. It was not possible to power the light source according to the specifications 6.4V, 130mA.

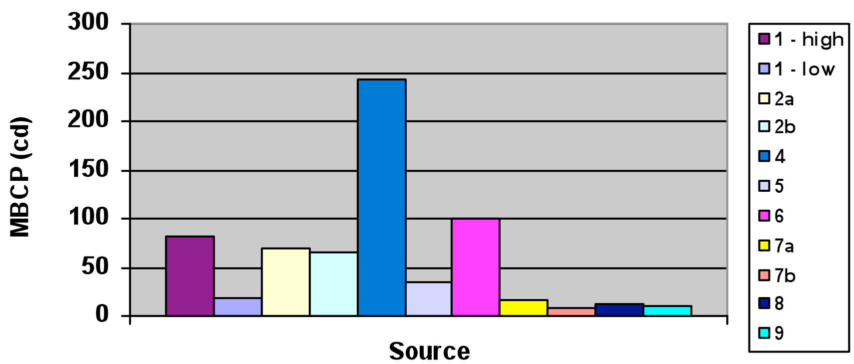

Figure 4: Distribution of maximum beam candlepower across 8 products tested.

Luminance and Glare

LED light sources have dramatically higher luminance than do standard light sources, which can result in uncomfortable--and even intolerable--intensity levels.[9] As the LED torches are expected to be used in darkness, in the absence of other sources of light, the potential for uncomfortable levels of glare was investigated, as well as the potential for damage to the eye.

[7] Values in parenthesis are illuminance values in footcandle units.
[8] Values in parenthesis are distances in feet.
[9] Sliney, David H. (1994) "Ocular Hazards of Light," *International Lighting in Controlled Environments Workshop*, T.W. Tibbitts (ed.) NASA-CP-95-3309.

Procedure

The luminance of each source was measured using a luminance meter, and a 1:87.5 neutral density filter. To begin testing, the standard lamp was used to ensure that the meter was within calibration range. Each source was located such that the LEDs filled the spot meter field of view, and luminance measurements were collected in a dark room.

To relate absolute measures of luminance to potential levels of visual discomfort, the IES glare index (GI), was evaluated for each source, where:

$$GI = 10 \log_{10} (0.5 \Sigma g), \text{ and}$$
$$g = 0.478 B_s^{1.6} \omega^{0.8} B_b^{-1} p^{-1.6}\ 0.478$$

With
B_s source luminance, in cd/m²
B_b average background luminance against which the source is seen, in cd/m²
ω angular size of the source in steradians as seen by the eye
p position index which indicates the effect of the position of the source on its capacity to produce discomfort glare

Table 7 relates GI to visual comfort regions. To estimate whether direct viewing of the sources might be hazardous, we computed the "Blue Light Hazard" weighted wattage for blackbody sources with color temperature equivalent to the LEDs in the study.

Table 7: Glare Index and corresponding visual comfort regions.

Comfort Region	Glare Index (GI)
Just perceptible	10
Noticeable	13
Just acceptable	16
Acceptable	19
Just uncomfortable	22
Uncomfortable	25
Just intolerable	28
Intolerable	>28

All of the sources tested are very bright as viewed from an on-axis line of sight, however it is expected that they will be positioned above a horizontal task plane, such that the source itself is only seen off-axis lines of sight. To quantify the directional intensity of each source, the set of illuminance measurements were supplemented to include off-axis illuminance, in increments of 2-5 degrees. These measures were collected using the procedure as in the illuminance testing, with the addition of a protractor to set the off-axis angle. The solid angle of each source was determined by measuring the dimensions of each LED, or array of LEDs, according to the geometry of the torches' optical design.

Results

The luminance and calculated GI values are provided in Table 8 and Figures 5-7. All the measured sources except 7a and 7b had a well defined beam with a beam half angle of 15 – 20 degrees. Sources 7a and 7b had a broad, less sharply defined distribution with a half beam angle of approximately 70 degrees. The direct glare index values were calculated at a background luminance of 1 cd/m^2 (which is close to darkness) while the edge of beam values were computed at the background luminance equivalent to an approximately 60% reflected surface illuminated from a distance of one meter from the source in question (2 – 50 cd/m^2).

We found that luminance varied by a factor of 60 for the products tested, and GI by 9 units in direct view, and 13 units at the beam edge. The GI values in Table 8 indicate that 6 of the 9 lamps had intolerable glare levels when viewed directly. This represents visual comfort and performance (e.g. ability to discern details) rather than safety. Figure 5 shows the distribution of luminance values for across each source tested, indicating that 7a and 7b were low-luminance outliers. Not surprisingly, the 7a and 7b sources were also the least glaring, although all the sources were unpleasant to view directly along their beam axis. Only source 6 was likely to be unpleasant to view at the edge of the beam. All the sources should be acceptable when viewed from outside their beam.

The computed blue-hazard wattage levels (a complex industry metric for lighting safety) were less than 0.001% of the hazard level, so no attempt was made to further refine the estimate, based on an assumption of black body color temperature equivalence.

Table 8: Luminance and Direct Glare Index.

Source	Luminance (cd/m^2)	GI (direct view)	GI (edge of beam)
1-low setting	201,000	28	18
1- high setting	761,000	32	21
2a	301,000	30	21
2b	236,000	30	21
4	163,000	31	15
6	499,000	31	24
7a	21,800	25	not measured
7b	12,300	23	11
8	759,000	29	not measured
9	188,000	27	not measured

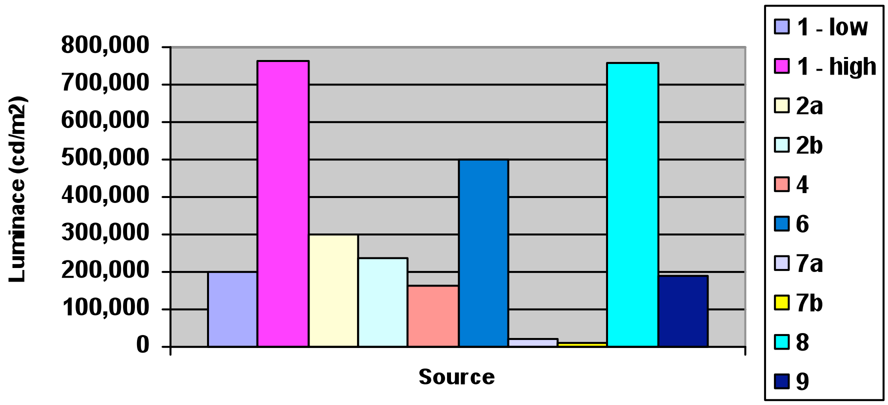

Figure 5: Distribution of luminance across 9 sources tested.

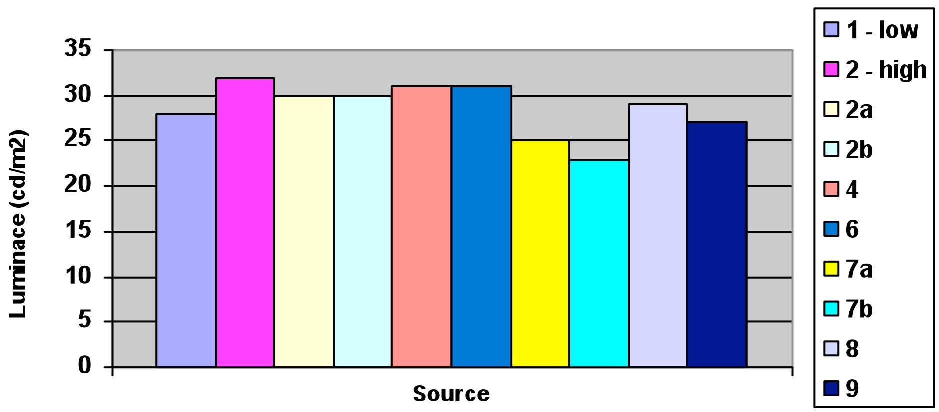

Figure 6: Distribution of direct view Glare Index across 9 sources tested.

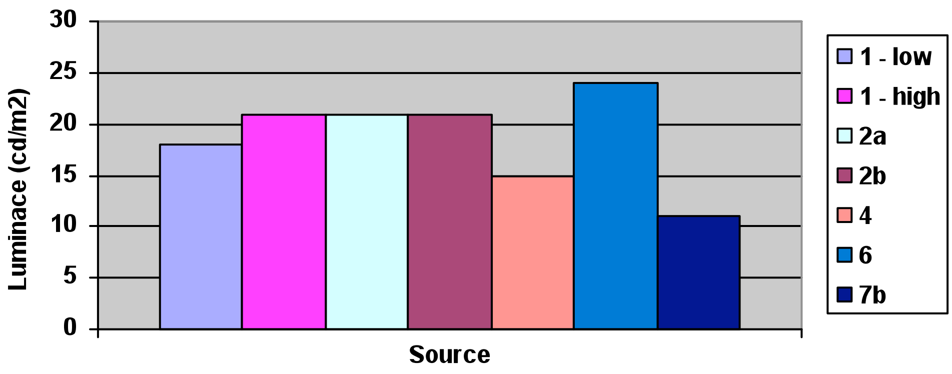

Figure 7: Distribution of beam edge Glare Index across 6 sources tested.

Potential Sources of System Inefficiency

Procedure

Two additional investigations were performed to attempt to identify potential sources of loss that could impact product performance. The type of ballast used in each product was identified by visually examining the internal circuitry and electronic components. Switching current regulators are the most efficient ballast type used in the products that were tested. Integrated circuit, and multiple components in the presence of an inductor indicate a switching current regulator. Resistor control is less efficient, and provides the poorest level of current control.

Constant current regulators are no more efficient than resistor control, yet provide much better current control; they are similar in appearance to the switching variety but do not contain inductors.

In addition to ballast efficiencies, optical losses were explored. Where the design permitted, the luminous efficacy of each functioning product was tested without optics and compared to the efficacy with optics.

Results

Tables 9 and 10 summarize products' ballast type and efficacy losses attributable to optic design. We found that optical losses varied by a factor of 3.2 for the products tested. Products 1, 8, and 9 used switching current regulators. Confirming the experimental findings, these were the also products that presented the power measurement challenges. With respect to optical design, product 2b was an outlier with significantly larger losses than the other products.

Table 9: Ballast type of each product tested.

Product	Ballast type
1	Switching current regulator
8	Switching current regulator
9	Switching current regulator
2a	Resistor current control
2b	Resistor current control
3	Resistor current control
4	Resistor current control
6	Resistor current control
7a	Resistor current control
5	Constant current regulator
7b	Constant current regulator

Table 10: Efficacy losses due to optics.

Product	Efficacy (lm/W)	Efficacy w/o optics (lm/W)	Percent Loss
1 – high setting	11.4	12.4	8
2a	39.2	43.0	9.5
2b	35.8	47.2	24 (foggy optics)
4	32.7	35.4	7.6
6	13.3	15.0	11

Further Research Needs

Through this work, we identified a number of further research needs. Several of the products targeted for analysis could not be fully tested because they failed during the process, in most cases due to readily recognizable manufacturing defects. In addition, the system efficiency investigation can be expanded. The findings related to losses due to optics can be broadened to include products that have reflectors, if not lenses, and the transmittance through the plastic lenses and optics in each product.

Given that several products did fail during testing, and that the anticipated off-grid environments may challenge product robustness, it would be valuable to include a durability assessment along with the optical analyses that are presented here. Finally, it would also be useful to develop a set of recommended design changes for poor-performing products.

Manufacturers of off-grid lighting systems would benefit from the establishment of a consistent, objective, and independent testing of product performance, particularly if coupled with constructive recommendations for improving product performance, durability, and consumer acceptance.