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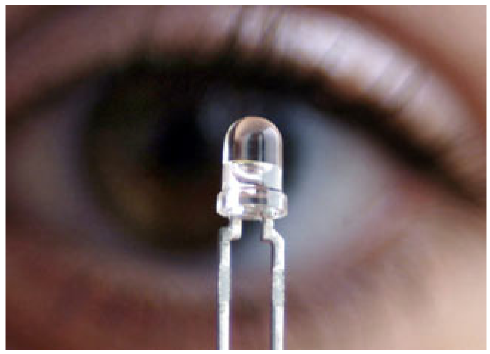
The Need for Independent Quality and Performance Testing of Emerging Off-grid White-LED Illumination Systems for Developing Countries



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The Need for Independent Quality and Performance Testing of Emerging Off-grid White-LED Illumination Systems for Developing Countries

Summary

White light-emitting diode (WLED) lighting systems have recently attained levels of efficiency and cost that allow them to compete with fluorescent lighting for off-grid applications in the developing world, were about 1.6 billion people still lack access to the electricity grid. Additional attributes (lower cost, compactness, ruggedness, and service life) make WLED systems potentially superior products. However, data characterizing the quality and performance of emerging WLED products are lacking, which creates an information deficit that can hamper market development. As a first step toward addressing this issue, we propose a suite of tests and consumer-oriented metrics and benchmarks for lighting services, usability, and economics that can be derived from these tests. While current trends are promising, our evaluation of a number of commercially available off-grid WLED lighting systems (lights plus batteries plus power sources) revealed wide variations in quality and disparities between manufacturer claims and actual performance. Specifically, we measured considerable variations in the quality and performance of the light sources, optics, storage batteries, electronic circuitry, and power supplies for WLED products from a variety of manufacturers and countries. For example, our tests of 260 5mm white WLEDs from 26 assemblers revealed a dramatic (five-fold) variation in efficacy (lumens per watt). Moreover, the performance *within* individual batches of identical sources varied by as much as 40%. There is a high risk of "market-spoiling" if inferior products are introduced and cause user dissatisfaction, especially if manufacturer claims overstate performance. Indeed, based on our findings from tests of products now in the market, some degree of spoiling is probably already occurring. Given the rising popularity of off-grid WLED lighting, the rate at which new products are being introduced, and the inception of major market-development programs, testing is urgently needed. If independently and consistently applied, such tests will provide policymakers, program designers, manufacturers, entrepreneurs, and consumers with complete and objective information needed to successfully deploy this technology. Quality assurance testing is also important for other parties, such as those seeking reliable and persistent greenhouse-gas reductions through the replacement of fossil-fuel-based lighting. In addition to presenting results of tests on specific products, we offer a recommended set of 14 test protocols that may be of use to those developing a more formal testing capability. These, in turn, inform a series of performance benchmarks that could be useful in developing standards or screening guidelines. In some cases, the tests we have defined may not be appropriate for use in a regulatory context, and we have not identified specific "pass/fail" performance criteria. Such work should be done in consultation with end users and other stakeholders.

Context

Illumination is a basic human need. It is a key ingredient for advancing literacy, safety, and the ability to do productive work. The number of people in the world without electricity—and hence electric light—has been rising for most of the past century. The International Energy Agency estimated the global number as 1.6 billion in the year 2000, and projected that it would stay approximately level through the year 2030 (Figure 1) as progress in electrification is offset by population growth and other factors. In sub-Saharan Africa—the most challenged region—IEA projects a substantial *rise* in the number of people lacking access to the electricity grid, with the number of people lacking access to grid electricity increasing from 500 to 650 million (30%) by the year 2020.

Although one in four people today obtains light at home exclusively with kerosene and other fuels, candles, or flashlights, they receive only 0.1% of the world's lighting energy services. Fuel-based lighting strategies are expensive and inefficient. This is exemplified by the case of kerosene lighting, whose users pay 150-times more per unit of useful lighting services than do those with the benefit of compact fluorescent lamps. In economic terms, the net result is that fuel-based lighting costs the world's poor $38 billion each year. Fuel based lighting also results in significant greenhouse-gas emissions in the form of approximately 190 megatons of CO_2 emissions. Efforts to address the issue clearly have immense potential benefits for equity, development, and the environment.[1]

Owing to the small size and dramatic improvements in the efficiency of white light-emitting diodes (WLEDs), it has become possible to create compact, highly affordable, rugged, and cost-effective illumination systems. These can be powered with small solar panels or other off-grid charging strategies, and they can operate using low-cost, rechargeable commodity batteries. These small and portable lighting systems can also be designed for grid-based charging. Here, users might charge the lights at existing fee-based grid charging shops. These shops are commonly used by people who lack electricity at home to charge devices ranging from cell phones to automotive style batteries that power TV sets.[2]

With proper optical control, WLED lighting systems can deliver adequate task illumination with one Watt or less of power input. Many WLED lighting products are coming to market in the $5 to $50 price range (depending on features, markups, etc.), which is significantly less than the $100 to $1,000 cost of solar-based fluorescent lighting systems that have been promoted in the developing world in recent years.[3]

Widespread use of off-grid WLED systems has the potential to enable a number of socially productive activities ranging from improved reading conditions for children to

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[1] The points noted in this paragraph are elaborated in Mills, E. 2005. "The Specter of Fuel-Based Lighting," SCIENCE 308:1263-1264, 27 May.

[2] Jacobson, A. 2007. "Connective Power: Solar Electrification and Social Change in Kenya," *World Development,* v35, n1, pp. 144-162.

[3] Nieuwenhout, F.D.J., van Dijk A., van Dijk V.A.P., Hirsch D., Lasschuit P.E., van Roekel G., Arriaza H., Hankins M., Sharma B.D., Wade H. 2000. "Monitoring And Evaluation of Solar Home Systems: Experiences with Applications of Solar PV for Households in Developing Countries," ECN-C--00-089.

improved lighting (and sales) for night-market vendors.[4] At the same time, to the degree that WLEDs displace fuel-based lighting, this technology can help deliver indoor and outdoor environmental benefits through reducing carbon dioxide emissions, and other consequences of fossil-fuel energy use.[5]

The Need for Quality Assurance

Realizing the potential of white LED technology for off-grid lighting on a long-term, sustainable basis, however, will require careful attention to issues of product quality and the real potential for a "market spoiling" effect in which end-users become disappointed and disillusioned if subjected to inferior products or those that simply do not perform as advertised. In some cases, downward pressure on pricing will increase the temptation for manufacturers to cut corners. In other cases, well-intentioned entrepreneurs will simply not be equipped to generate appropriate designs and conduct in-house testing to assess performance.

Experience from the Kenya solar market, which is among the largest and most dynamic per capita among developing counties, provides a sobering reminder of the need for performance standards and quality assurance mechanisms. While most solar modules sold in the country perform near advertised levels, the persistent presence of several low-quality brands has reduced consumer confidence and slowed sales growth for more than a decade.[6] In a promising turn of events, the Kenya Bureau of Standards began enforcing regulations related to the performance of amorphous silicon solar photovoltaic (PV) modules in 2005. This long overdue effort, which involves solar module testing and certification by internationally recognized laboratories (e.g. the International Electrotechnical Commission, IEC), appears to have significantly reduced the market presence of the lowest performing brands.[7] Thus, although some quality and performance problems remain, the success of the current regulations in Kenya indicates the importance of testing, certification, and enforcement in efforts to ensure quality and protect the public interest.

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[4] While it is likely that off-grid WLEDs will be used for these and similar applications, there is no guarantee that any specific set of "socially productive" uses will be among the most prevalent applications of the technology. As is true with all technologies, the social uses of off-grid WLEDs will depend on multiple factors, including product performance and affordability, the incomes of potential end-users, and intra-household relationships, as well as a host of broader social, economic, and cultural processes. See Jacobson (2007) for a related discussion of solar electrification in Kenya (see Jacobson, 2007. *op cit.).*

[5] Note that it is difficult to predict the level of CO_2 emissions reductions that may result from the use of off-grid WLED systems. Actual emissions reductions will depend on the degree to which the use of WLEDs displaces, rather than adds to, kerosene and other forms of fuel based lighting. The most likely outcome may be that WLED systems will become a partial substitute for fuel-based lighting. That is, end users that adopt the technology will continue to use kerosene lighting in parallel with WLED lighting. In these cases, WLEDs may displace some, but not all, of the fuel based lighting in a household or business (meaning that lighting service levels are increased to some degree in exchange for reduced energy savings). Well-performing products will have the greatest potential for achieving emissions reductions.

[6] Duke, R.D., A. Jacobson, and D.M. Kammen. 2002. "Product Quality in the Kenya Solar Home Systems Market," *Energy Policy*, 30, 477-499.

[7] Jacobson, A. and D.M. Kammen, 2007. "Engineering, Institutions, and the Public Interest: Evaluating Product Quality in the Kenya Solar Photovoltaics Industry," *Energy Policy*, 35, 2960-2968.

Product quality has also been an issue for fluorescent and incandescent light sources.[8] Compact fluorescent lamps (CFLs) have exhibited a wide range of performance, as indicated by a recent survey conducted in seven countries in the Asia-Pacific region. In these nations, low-quality CFLs represented from 7% to 34% of total sales.[9] This issue has been among the primary reasons for the creation of national and international campaigns—notably the Efficient Lighting Initiative, ELI—to ensure CFL quality via testing, labeling, and other methods.[10]

Similarly broad efforts are needed to ensure quality in emerging markets for off-grid white LED products. It is our hope that early, pro-active steps to ensure quality can help minimize the types of problems associated with the sales of under-performing products that have troubled solar lighting markets in the past. This work is necessary not only to avoid market spoiling, but also to protect the interests of millions of low-income families who may experience very real financial losses from the purchase of inferior goods.

At present there is virtually no publicly available data on the quality and performance of WLED lighting systems for off-grid applications. There are also no comprehensive public-domain test procedures for off-grid WLED lighting systems, although many tests are being developed for individual components.[11] Key areas of concern include the performance of batteries, power supplies, and the lights themselves, as well as the quality of associated optical systems. As we describe below, our initial performance results for commercially available off-grid WLED products and components indicate considerable cause for concern.

Performance of WLED Products

This new generation of technology appears quite simple at first, yet has many components and sub-systems that can suffer from performance problems. Off-grid WLED lighting systems include the following important elements.

1. Illumination, which includes the light sources, associated optical controls (lenses, reflectors, diffusers), and positioning of the light with respect to the desired task.
2. Power supply, which includes either a grid-independent charging system (e.g. photovoltaic cells) or an interface with the grid for charging.
3. Energy storage and power management, which typically involves batteries, battery charging electronics, and the circuitry for regulating and delivering power to the light source. In some cases, capacitors may be used for storage in systems that involve mechanical crank, pump, or shake type micro-generator charging systems.

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[8] Fu Min, G., E. Mills, and Q. Zhang. 1997. "Energy-Efficient Lighting in China: Problems and Prospects," *Energy Policy* 25 (1): 77-83. see http://eetd.lbl.gov/emills/PUBS/china.html

[9] duPont, P. 2006. "International CFL Market Review: A Study of Seven Asia-Pacific Economies," Australian Greenhouse Office. (August)

[10] See http://www.efficientlighting.net/

[11] A major effort in this regard is being orchestrated by the U.S. Department of Energy, Building Technologies Program. See http://www.netl.doe.gov/ssl.

In addition, all of these elements must be integrated into a complete system that includes electrical switches, a housing enclosure, possibilities for mounting or hanging the lamp, et cetera. These system components influence performance characteristics such as durability and resistance to environmental conditions (temperature, humidity, insects, etc.). They also influence the way the product is used (e.g. orientation towards the sun in the case of solar charging), which, in turn, may influence "as-used" performance as distinct from performance under standardized, ideal laboratory conditions. Figure 2 provides a conceptual description of a WLED system.

The purpose of this report is to develop test procedures and apply them in an illustrative fashion. Future work will evaluate specific products more systematically and in greater detail. Figures 3 through 14 provide examples of the performance of a cross section of commercially available WLED systems and components based on our tests. Figures 15 through 17 illustrate how these results can be used to derive consumer-relevant indicators such as total cost of ownership. In each case, the results are based on our original measurements of commercially available products. It should be noted that there are various classes of products, e.g. ambient lights, task lights, and portable way-finding lights (flashlights or torches), each intended for a different purpose. This should be taken into account when comparing products and test results. For example, a flashlight should give a narrow-beam light distribution whereas an ambient light should give a more diffuse distribution.

Performance of White LED Light Sources

A natural starting point for evaluating product quality is with the individual white LED light sources likely to be incorporated into integrated systems. While a number of reputable companies produce high-quality white LEDs, our measurements confirm that some products available in the market perform well below expectations.

Figure 3 shows the variation in performance for 260 individual off-brand LEDs. These samples, which were obtained in batches of 10 LEDs each, were collected from 26 "packagers" and "traders" in the Shenzhen region of China who assemble chips, phosphors, and optics into functional devices and distribute the systems to wholesale buyers.[12] These are representative of the types of LED products encountered by many firms that are designing and assembling complete lighting systems. Our measurements show dramatic variations in lamp characteristics across the entire sample. The efficacy of the LEDs ranged from approximately 12 to 60 lumens per Watt. This 5.1x range is the result of variations in the light output (5.0x) and power consumption (1.3x).

We also observed a remarkable degree of variation *within* the 26 individual batches of that had been represented by the respective vendors as "identical" (Figure 4). The luminous efficacy of the most efficient subsets of the LEDs that we tested is exceptional (equal to or better than most compact fluorescent lamps), while the performance at the

[12] For more details, see E. Mills. 2007. "Assessing the Performance of White LED Light Sources for Developing-Country Applications," The Lumina Project, *Research Memo #1*, Lawrence Berkeley National Laboratory, http://light.lbl.gov.

low end is no better than the common incandescent lamp. It should be noted that a recent report from the U.S. Department of Energy indicated a much narrower range of luminous efficacies, perhaps reflecting tests limited to brand-name products.[13]
We also evaluated the color characteristics of the LED samples.

Surprisingly, despite the large deviations in luminous efficiency, the quoted prices did not vary appreciably among these products. This indicates a form of information market failure in which prices do not reflect the value of the available products.

Color Rendering Indices (CRI) were largely quite good (on a par with those for compact fluorescent lamps), with an overall range from 69 to 91. The range was similar (72 to 90) for the Color Quality Scale, CQS,[14] which is an alternate metric that some prefer over CRI for evaluating LED light sources. Correlated Color Temperature (CCT) measurements were extraordinarily variable, with most of the products presenting a strongly blue profile. The "warmest" value was over 7000 degrees Kelvin, which is higher than that found among most conventional fluorescent light sources. Lowering the CCT into a "warmer" zone would likely reduce the efficacy of the LED light sources. Variation within batches was again significant in many cases (Figure 5). There was no observed correlation between luminous efficacy and CRI, CQS, or CCT.

The results presented in Figures 4 and 5 indicate a wide range of performance even within a given vendor's products. This pattern may be the result of a manufacturer screening process. That is, the units we tested may be discards from orders where the on-spec units were isolated by the manufacturer for sale to a particular customer, and the leftovers were aggregated together for bulk sales to downstream vendors seeking low-cost components.

These performance variations raise concerns about the potential for "market spoiling." Many of the companies that integrate LEDs into complete off-grid lighting systems may be poorly equipped to screen for quality. As a result, the lighting products that they deliver to market are likely to have corresponding variations in performance. Consumers unlucky enough to purchase a low performing unit may reject the technology, and the overall reputation of WLED systems could suffer.

[13] U.S. Department of Energy, Office of Building Technologies. 2006. "Energy Efficiency of White LEDs," Available online: http://www.netl.doe.gov/ssl/PDFs/energyEfficiency_oct25_06.pdf

[14] Davis, W. and Y. Ohono. 2005. "Toward an Improved Color Rendering Metric," *Proceedings of the Fifth International Conference on Solid State Lighting,* edited by Ian T. Ferguson, J. C. Carrano, T. Taguchi, I. E. Ashdown, *Proc. of SPIE* Vol. 5941 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.615388.

Illuminance Characteristics of Commercially Available White LED Lighting Systems

We also observed considerable variations in lighting performance among commercially available off-grid WLED products. These are products that integrate individual LEDs such as those just discussed with energy conversion, charging, storage, and optics subsystems to deliver illumination with a particular intensity and distribution. Figure 6 indicates that the illuminance (in lux, or lumens per square meter) levels of these systems vary quite widely. The measurements were made at a distance of one meter from the light source, and include illuminance levels at the peak (or center-line) of the lamp's "beam," as well as at a point that is 10 cm from the center-line. The illuminance level at the centerline provides an indication of the intensity of the light's output, while the degree of difference between the illuminance at the two points for each device is a function of the optical properties of the respective lamps. In the case of two products, we measured illuminance for five "identical' samples and found a 25% variation.

In many applications, the utility of a lamp is a function not only of the intensity of the light it delivers, but also of the distribution of illuminance on a working surface. Figure 7 shows the three-dimensional spatial distribution of illuminance over a 1-square-meter area at a distance of one meter for two lamps (Systems 7 and 15 from the set compared in Figure 6). The product on the top achieves a relatively uniform distribution that is appropriate for reading and other task lighting applications. In contrast, the product on the bottom creates a distribution that is highly concentrated. This distribution may be appropriate for a flashlight, but it is considerably less favorable for a task such as reading. The differences between the distributions are the result of the choice and spacing of the WLEDs and the choice of optics.

The results presented in Figures 8 and 9 provide additional metrics for comparing the distribution of illuminance for different lanterns. The results are intended to highlight the importance of an even distribution for reading and other similar tasks. Diffusers, LED spacing, reflectors, and other optical devices can be used to achieve an even distribution of illumination (in addition to the optical properties of the particular LED specified for the product).

Figure 10 presents a candlepower distribution for an early solar-WLED lighting product (System 3, with lens; and System 4, without lens). The candlepower distribution represents the geometry and intensity of light emanating *from* the light source (as opposed to the delivery of light to the working surface, as measured using a goniophotometer). The results shown in the figure represent vertical sections at 30-degree axial intervals, and indicate considerable asymmetry in the product's lens. This will translate into non-uniformity in the intensity and geometry of the pattern of illumination at the task surface. With a uniform lens, the traces shown in the figure would be coincident. Candlepower distributions can be obtained for individual WLED light sources, or for assemblies.

Performance of Energy Storage and Power Management Sub-Systems

Although it may be tempting to focus solely on the lighting and optical elements of off-grid white LED lamp performance, energy storage and power management are equally important.

Batteries provide the most common form of storage. In the case of rechargeable batteries, product manufacturers must select from a range of battery chemistry types, including sealed lead acid (SLA), nickel cadmium (NiCd), nickel metal hydride (NiMH), and Lithium Ion (Li-ion). Each battery type has different operation, performance and price characteristics that influence its suitability for a particular product line. For example, SLA batteries have a low price per unit of storage capacity, but their sensitivity to overcharging, deep discharge, or being left in a discharged state often leads to a relatively short operational life time ("service life"). Two of the primary alternative options, NiCd and NiMH batteries, are less sensitive to overcharge and deep discharge, but they cost considerably more per unit of storage. See Table 1 for a summary of typical characteristics for each battery type.

Measurements of the storage capacity of batteries from two types of commercially available off-grid WLED lamps reveal a range of performance levels. The results in Table 2 indicate that one brand of SLA batteries (used in System 7) performed considerably below advertised levels, while the NiCd batteries that we tested (used in System 15) exceeded their rated specifications. These results are for a limited set of products, so they do not provide a basis for drawing definitive conclusions on the efficacy of different battery chemistry types for off-grid WLED applications. They do indicate, however, that batteries used by some WLED product assemblers do not perform as advertised.

Battery capacity is measured by discharging a fully charged battery at a constant current rate. Figure 11 shows discharge curves for two of the batteries from the product lines presented in Table 2. The SLA battery represented by the upper curve in the graphic delivered only 80% (640 mAh) of its 800-mAh advertised capacity, well below its rated specifications. In contrast, the NiCd battery, which was also rated to deliver 800 mAh, exceeded its specifications by delivering 893 mAh.

While many off-grid WLED lamps are designed to operate exclusively with rechargeable batteries, some can be powered using disposable alkaline batteries. Rechargeable batteries offer considerable advantages over disposable batteries in terms of the life cycle cost of operating a WLED lamp, but first-cost hurdles will lead some buyers to utilize disposables. It is, therefore, useful to compare the performance of WLED products using a variety of types and brands of disposable alkaline batteries.

Figure 12 provides comparative service-life indicators for two brands of AA alkaline batteries (the most common type of battery specified for off-grid LED lighting systems). These trials show that not only do lower-quality alkaline batteries (purchased in Kenya) result in curtailed initial light output (25% in this case), but also significantly shorter

service life. Using the point at which initial light output depreciates to 50% of the initial output as an end-of-life benchmark, the higher-quality batteries lasted approximately six-times longer, providing approximately eight-times the total luminous flux. Unfortunately, in some areas low performing alkaline batteries are the only type available to end-users. In other cases, higher quality alkaline batteries are present, but their cost per battery is considerably higher than their low performing counterparts and users may not be aware that life-cycle costs are higher. While WLED systems may be shipped with high-quality batteries, the availability of comparable replacement batteries in the destination markets must be considered.

Whether a lamp utilizes rechargeable or disposable batteries, the electronics that regulate the delivery of electricity to the LEDs play a key role in determining lamp performance. Some of the lamps that we tested had very minimal circuitry. As a result, the current to the LEDs and the corresponding light output vary widely with changes in battery voltage. Other lamps included circuitry to regulate the current output so as to maintain relatively constant light output over a range of battery voltages. While including circuitry to effectively regulate current to the LEDs does add to the cost of the system, the benefits in terms of consistent light output over time may be considerable.

The performance curves in Figure 13 show battery voltage, current draw, and illuminance at a distance of 20 cm for two different battery powered WLED lamps (Systems 7 and 15). The upper figure, which corresponds to a product with minimal circuitry, indicates the aforementioned rapid decline in illuminance over time. The performance results for the lamp in the lower figure, in contrast, indicate relatively constant illuminance over a period of nearly 10 hours. In addition to indicating the importance of voltage regulation circuitry, these curves also highlight the value of testing WLED product performance over a full discharge cycle. Tests that merely measure the lighting output when the battery is fully charged may overstate the performance of some WLED products.

Performance of Charging Systems

The batteries used in off-grid WLED products can be charged using several different methods. In many cases, products are designed to be charged using a small solar PV module (e.g. 0.5 to 5 Watts). Other products are charged using standard AC electricity, while still others are charged by integrated mechanically driven micro-generators. In each case, the charging system may include a power source, charge regulation circuitry, and some form of end-user feedback that provides information such as the state of charge.

The charge regulation requirements of batteries vary by chemistry type. In each case, the use of an appropriately designed charge regulation circuit can increase performance and battery life. As noted above, sealed lead acid batteries, while inexpensive, have the disadvantage of being particularly sensitive to both over-charging and deep discharge. Failure to incorporate proper regulation circuitry into the system can shorten SLA battery life significantly. Nickel cadmium, nickel metal hydride, and lithium-ion batteries are also sensitive to over-charging, but none of these three types are negatively affected by deep discharge in the way that SLA batteries are.

The charging system for WLED products can be evaluated through measurements that determine the performance of the power source, as well as tests that reveal information about the charge regulation circuitry.

Figure 14 provides performance results for two photovoltaic modules used as power sources in one particular WLED product line (System 15). The results in the figure indicate that the module used to power one of the nominally identical samples performed considerably better than the other. We tested a total of six modules from this product line. The average power output at standard test conditions of 1000 W/m^2 and 25ºC was 0.49 Watts, and the standard deviation was 0.08 Watts (~15%). These findings indicate considerable variability in power output from the solar charging sources in the product line. A consumer unfortunate enough to have purchased a lamp with the lowest performing module would experience charging times that were about 30% longer.

We examined two low-cost hand-cranked flashlights, and found a very rapid decline in light output. One product, represented as data-points 26 and 27 in Figure 6, exhibited a 90% reduction in illuminance within 10 minutes of fully charging. The second product, represented as data-points 28 to 30, exhibited a 60% reduction in 10 minutes, and almost complete discharge with in 30 minutes.

Other System Parameters and Characteristics

In addition to the sub-systems described above, the performance and utility of WLED lighting products are influenced by a variety of additional parameters, including ease of use, form factor, appearance, shock resistance, durability, degree of dust and moisture resistance, and others. Each of these parameters should be considered when designing and evaluating lighting devices.

WLED Product Testing Protocols

Table 3 presents a set of tests that can be used to characterize product performance and quality, and cross-references these tests to the results in this report. Table 4 describes the test equipment and conditions used to perform our analysis. In most cases, the tests involve short-term evaluations of the performance of devices when they are "new" (e.g. tests #1-5, 7-9, 11-15 in Table 3). These measurements may prove to be the most practical for quality screening, as they do not require testing over an extended period of time. An additional set of tests provide valuable information about the long-term performance of WLED products (e.g. tests #6 and #10). These measurements are important, but may prove to be expensive to implement in the context of standardized evaluations of product quality.

In all cases, tests should be conducted at standardized conditions, and many should be replicated in "as-used" or field conditions. The latter should include geographic variables such as solar insolation, and application variables such as distance of light from task as well as evaluation in adverse conditions, e.g. extremes of humidity, temperature, dirt, and

handling. It may also be advisable to test products with a standardized battery so as to isolate the effect of that subsystem on overall performance. With respect to illuminance, the delivered light levels will be a function of the working distance from the source to the task area. We have standardized most of the measurements reported here to a one-meter working distance.

In some cases, "as-used" performance will vary sharply from standard test conditions. Notably, the performance of most components (e.g. LEDs, batteries, and solar cells) will vary with temperature. In addition, we have observed that the advertised performance of some products is based on idealized assumptions about in-field use patterns. For example, the time to charge the battery in a WLED product using solar energy depends on the orientation of the modules towards the sun. While "time to charge" estimates are often based on standard laboratory measurements for ideal (direct-normal) orientation, many end-users may leave the solar PV module in locations and orientations that are far from optimal. In some cases, suboptimal orientation is inadvertently dictated by the design of products we evaluated. As a result, end users may experience charging times that are much longer than those advertised by manufacturers and vendors. As an illustration, if System 15 is left to charge in a horizontal position (so that the panel is facing upwards) for an average day in Luanda, Angola[15] the user will be able to use the lamp for about 5 hours each day. If, on the other hand, the lamp is left to charge in a free-standing vertical position (with the solar panel oriented in a south-facing vertical surface) under standardized test conditions of 1000 W/m2 and 25°C, the solar input reduces the time of operation to 1.8 hours per day. If the lamp is left in a vertical position so that it is not facing due south or if there are partial obstructions (e.g. if it is inside a room on a window sill), then the solar input will be reduced still further.

There are also useful ways to aggregate test results to enable consistent relative performance and quality comparisons by potential buyers and policymakers. Figures 8 and 9 provide two examples that readily convey the variability in performance among WLED product lines. The graphics put the results in context by relating them to normative guidelines or practical user needs such as the level and uniformity of illumination over an area the size of a sheet of paper.

The Role of Test Procedures in Market Transformation

Our preliminary observations indicate large variations in product performance and quality both among and within WLED product lines. Market spoiling is thus a real risk if products are deployed in the field without adequate screening, and adopted by end users without adequate information about the products' attributes.

Precedents exist for voluntary or mandatory standards to enhance end-use energy efficiency, most notably building energy codes and appliance and equipment efficiency

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[15] The following calculations assume that the average solar energy on a horizontal plane for Luanda is 5.5 $kWh/m^2/day$. The estimates for performance when the lamp is positioned vertically are based on standard solar geometry equations from Duffie and Beckman (2006) *Solar Engineering of Thermal Processes, 3rd Edition*, John Wiley & Sons.

standards. The development and acceptance of such standards is predicated on the establishment of test procedures such as those described here.

The availability of standard test procedures can also support manufacturers' product development efforts and competitive analysis. In this case, manufacturers might use the procedures to evaluate progress towards achieving higher quality by comparing the performance of their products with established benchmarks. The development of the WINDOW software[16] for evaluating the energy performance of efficient window design options provides one successful example of this approach.[17]

Testing can also form the basis for efforts to disseminate information about the comparative performance of products through channels such as trade magazines and product labeling. As noted above, traditional solar photovoltaic collectors became more consistently efficient in Kenya, thanks in part to the public availability of product performance information.

In some cases, quality assurance test methods for WLED products can be based, at least in part, on existing standards. For example, the Photovoltaic Global Approval Program (PVGAP),[18] has adopted a set of standards that for off-grid solar PV systems and associated components. Some of the test methods associated with this program may be appropriate for testing associated with WLED products. At the same time, it will be important to develop a standardized quality assurance test regime for off-grid WLED products that balances thorough and rigorous testing of a range of system parameters with cost considerations. Here, it is important to ensure quality without making the cost of testing overly burdensome to manufacturers.[19] High-cost testing can be less successful than a more moderate approach for at least two reasons. First, small firms may be unable to afford the entry costs associated with high cost testing. Second, an expensive test regime may encourage some manufacturers to simply avoid markets where quality assurance is required.

Given that many countries and markets may not adopt standards or guidelines in the near term, an overly expensive test regime could result in reduced competition and innovation in markets where compliance with performance standards is required. A test regime that successfully balances rigor with cost has the potential, therefore, to result in the most optimal path to large markets for high quality off-grid WLED lighting products. The cost of equipment utilized in the testing described in this report (see Table 4) was around US$15,000. Imposing tighter requirements on equipment precision and accuracy would elevate these costs sharply. The time necessary to establish an experimental setup and perform the tests is a function of skill level and experience.

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[16] See "WINDOW 4.0: Documentation of Calculation Procedures." 1993. E.U. Finlayson, D. K. Arasteh, C. Huizenga, M.D. Rubin, M.S. Reilly, Lawrence Berkeley National Laboratory Report No. 33943.

[17] See http://www.nfrc.org/ and http://www.efficientwindows.org

[18] See http://www.pvgap.org/

[19] See Duke, R. D., A. Jacobson, D. M. Kammen. 2002. (*op cit.)* for a discussion of this issue in the context of developing country solar PV markets.

Practical Metrics for Consumers

Laboratory measurements are most useful if translated into metrics that have practical meaning for end-users, and provide performance benchmarks for product manufacturers or intermediaries between manufacturers and end-users. Such metrics would characterize lighting quality, usability, and economics. In some cases, these metrics could be customized to reflect local conditions (e.g. solar availability, time of year, battery prices). In the list below, we outline eight examples of metrics that can be derived from the tests that we outline in this paper.

1. Lighting services
    a. **Illuminance delivered to a surface in relation to a pre-defined goal/target.** The value varies inversely with the square of the distance between the light and the sensor. This metric draws from test #4 in Table 3. Standards vary widely among countries.[20]
    b. **Spatial variation of illuminance delivered to a surface.** This metric can be expressed in the form of the ratio of center-line to off-line illuminance. The result, which provides a sense of lighting uniformity over a given task area (e.g. reading), can be derived using measurements from test #4 (and illustrated such as is done in Figures 6 through 9). Variability (and absolute illuminance) will decline as the light is moved farther from sensor.
    c. **Hours of useful illumination delivered from a fully charged battery.** This metric would be derived by applying a decision rule to the results from test #5, e.g. useful operation time until 50% of initial light output is reached.
    d. **Color qualities of the light** as measured in test #7. The color rendering can be compared to benchmark values.

2. Usability
    a. **Days to charge the battery in solar-based products.** This metric would combine information from test #9 (storage battery capacity) and #12 (solar module performance). Some products that we have encountered cannot be charged in a single (sunny) day. Note that this metric should be adjusted to account for local solar conditions.
    b. **Frequency of charging as a function of desired hours of light per day.** This metric draws from tests #5 and #9. This metric is used to develop the battery charging and replacement cost elements of cost-of-ownership metrics such as those in Figures 15 through 17.

3. Economics
    a. **Cost to purchase and operate the system over a fixed period (e.g. one year) or its useful lifetime, often referred to as "total cost of**

[20] Mills, E. and N. Borg. 1999. "Trends in Recommended Lighting Levels: An International Comparison," *Journal of the Illuminating Engineering Society of North America* 28(1):155-163. http://eetd.lbl.gov/emills/PUBS/PDF/Light_Levels.PDF

ownership". This metric incorporates information about the initial costs to purchase the lamp, as well as ongoing costs including battery charging and replacement. The analysis can be informed by measurements from tests #5 and #10, as well as price data and information about patterns of use by end-users. The result can be compared to the total cost of ownership for alternative lighting systems, such as kerosene lamps or compact fluorescent-based lanterns. Figures 15 and 16 indicate application of these metrics to a variety of commercially available WLED lighting products.

b. **Cost per unit of service.** This metric could be formulated in a number of ways, e.g. annualized cost of ownership versus peak illuminance (Figure 17), purchase price versus average illuminance over a designated area, etc. Note that—in this example—there is little evidence of a correlation between cost of ownership and service level.

To apply these metrics in the process of product evaluation or selection requires the establishment of normative targets such as acceptable light levels, variability of illumination across the task plane, peak luminance (related to glare), lumen depreciation during the discharge cycle, battery quality and durability, and others. Establishment of such targets is an important area for future work. This work should be done in consultation with end users and other stakeholders. In consideration of cultural and economic factors, targets should not be simply transplanted from levels that have been adopted in industrialized countries.

Conclusions

Component and system testing and benchmarking of emerging white-LED illumination systems provides critical "market intelligence" about quality and performance. It can also inform efforts to develop standardized quality assurance protocols through broader efforts to promote the technology in the developing world. Some providers of off-grid WLED systems lack the capability or skill required to design and conduct acceptance testing for their products and are thus susceptible to non-disclosed corner cutting by their component suppliers manufacturing agents.

We conducted illustrative tests on samples from the first generation of commercially-available grid-independent white-LED lighting systems, and found that some products perform adequately while others perform well below advertised or acceptable levels. The results are likely representative of variations in the broader array of WLED products that are increasingly being introduced in the developing world.

Our results show that it is clearly possible to build high-quality, high-performance LED systems for the developing world. However, our analysis also raises important questions for those who wish to sell white LED lighting systems to quality-conscious customers, for entrepreneurs seeking white LED light sources for inclusion in products, and for policy makers and other entities designing or evaluating initiatives to scale up the delivery of grid-independent lighting systems for this market.

Vendors of LED lighting products in the developing world have indicated a desire for the independent development of such procedures, which can help them benchmark, improve, and market their products. It is more economically efficient and credible to create a centralized and neutral testing capability than to impose these costs on individual manufacturers. Products currently sold in target markets, as well as those being made in prime manufacturing countries (e.g. China, India, France, USA) should be evaluated. An ongoing testing capacity should be maintained, as this family of products is in a highly dynamic state of development, and a steady stream of new producers are entering the market. As an example of the first point, Systems 3 and 5 (see Figure 6) are two generations of the same product, separated in time by only a year or two. Between these two product cycles, peak illuminance increased four-fold. Some producers may improve their products in response to test results—or standards informed by test procedures such as those described here—and this progress should be tracked and the improvements independently evaluated.

Our results are indicative rather than comprehensive. A wider variety of LED product samples should be independently tested; there are likely some that perform outside the bounds of the (already wide) range we have observed here. Multiple units from each product line should also be tested to ascertain the degree of consistency in product specification and manufacturing. Additional testing of the light sources should focus on life testing.

Product testing protocols should be informed by market research on end-user needs. A particular design may operate with high efficiency in an engineering sense, but deliver a level or pattern of light distribution, duration of output, etc. that fails to meet the intended end-users' needs. Field conditions may also differ from laboratory test conditions, and improved understanding of these factors should be used to develop "as-used" test procedures and metrics to complement those developed in a laboratory setting. Testing can be used to verify manufacturers' claims, but can also be used to identify best practices and to define desirable performance targets.

Given the rising popularity of the LED lighting concept for developing countries, and the impending launch of major deployment programs,[21] there is a specific urgency to formalize a product quality and performance testing process, and ensure that the results reach key audiences. The failure to do so will invite market-spoiling problems that will ultimately inhibit the penetration of good products and the achievement of significant energy, economic, and environmental benefits. Indeed, this process may already have begun.

[21] http://www.ifc.org/led

Table 1. Summary of Typical Characteristics for Different Types of Rechargeable Batteries

Battery Type	Nominal Voltage (volts/cell)	Storage Density (Wh/kg)	Auto-Discharge (%/month)	Relative Pricing
Seal Lead Acid	2.0	30	5-10%	Low
Nickel Cadmium	1.2	40 to 60	25%	Medium
Nickel Metal Hydride	1.2	60 to 80	25%	Medium High
Lithium Ion	3.6	90 to 150	8%	High

Sources: Dallas Semiconductor Maxim, Application Note 3501, "Rechargeable Batteries: Basics, Pitfalls, and Safe Recharging Practices," March 21, 2005, www.maxim-ic.com/an3501; Dallas Semiconductor Maxim, Application Note 3999, "Overview of Rechargeable Batteries and Fast Stand-Alone Chargers," February 13, 2007, www.maxim-ic.com/an3999.

Table 2. Performance Results for Two Particular Sets of Storage Batteries Used in WLED Lighting Systems (SLA = System 7; NiCd = System 15)

Battery Chemistry	Nominal Voltage	Rated Capacity (mAh)	Discharge Rate (hours)[22]	n	Average Measured Capacity (mAh)	Percentage of Rated	Standard Deviation (mAh)
SLA (sealed-lead-acid)	4.0	800	20	5	680	85%	77
NiCd (nickle cadmium)	3.6[23]	800	1	6	892	112%	28

[22] The discharge rate is used to specify the current that will drain the battery completely in the indicated number of hours. SLA batteries are commonly rated for a 20 hour discharge, while NiCd and NiMH batteries are commonly rated for a one hour discharge.

[23] This lamp used a battery pack that consisted of three AA size NiCd batteries that were configured in series. Each battery has a nominal voltage of 1.2 volts, so the overall voltage of the cell was 3.6 volts.

Table 3. Summary of Proposed Test Procedures for White LED Products*

#	Test Procedure	Metric	Notes
ILLUMINATION SUB-SYSTEM			
1	Luminous Flux	Lumens	Total lumen output for system (captures effects of power supply ("driver"), optics, and light source). Measurement of total luminous flux is made with an integrating sphere. Use of goniometer allows also for characterization of light-distribution pattern.
2	Light Source Luminous Efficacy	Lumens/watt	Ratio of the results of Test 1 to power delivered to light source, independent of the device and optics in which the LED is mounted.
3	Luminaire Efficiency; Luminaire Efficacy	%; lumens/watt	Ratio of luminous flux from Test 1 to sum of light emitted from LEDs in test 2; Ratio of luminous flux from Test 1 to power input.
4	Light Distribution Uniformity	Array of lux measurements in in three dimensions	Measurement of the production, extraction, and distribution of light output of entire system (source + optics). Measurements of the light source using a goniometer as well as the illumination incident on a task surface are both useful. Relatively uniform distributions are preferable for reading and task lighting applications. See Figures 7-9.
5	Light output over a single discharge cycle	Lux as a function of time; Discharge cycle	Measurement of the light output, voltage and current draw of the lamp during discharge of battery.. See Figure 13 for an example.
6	Long-Term Light Output	Lux as a function of time; Lamp Life	Measurement of lamp lumen depreciation over time. High-quality LEDs can maintain high lighting levels for tens of thousands of hours, while the output of lower quality products declines much more rapidly. These longer-term measurements can require 12+ months.
7	Color	Correlated Color Temperature; Color Rendering Index; Color Quality Scale	Measurement of the color-quality of the light sources. See Figure 5 for an example.
8	Glare	Luminance	Measurement of the intensity of light from the source itself. This is important given the small size of LED lights and their corresponding brightness, which can cause discomfort glare as well as injury if users look directly into the light.
ENERGY STORAGE SUB-SYSTEM			
9	Storage Battery Capacity	Ampere-hours	Primary measurement of battery size (in ampere-hours). The measurement is made by discharging the (new) battery fully at a constant current. The result is compared to the advertised battery capacity. See Figure11 for an example.

#	Test Procedure	Metric	Notes
10	Battery Cycle Life	Persistence of battery capacity	Primary measurement of battery performance over time. Each battery is charged and discharged at rates that approximate actual operating conditions until the battery storage capacity drops to 50% of its original capacity. These measurements are critical for evaluating the longevity and life cycle cost of off-grid WLED products. Measurements can last 2-12 months or more per battery, and equipment limitations can restrict the number of batteries that may be tested at one time.
11	Storage Battery Charging	Performance of charging system	Measurement of voltage, temperature, and current input to the battery during charging. This test provides information about the electronic circuit used to regulate charging in the WLED device, as well as the potential for damage to the battery due to over-charging or high temperature. The test can be carried out multiple times with different charging sources as applicable (i.e. charging with grid and/or solar). Outside air temperature should be measured at the same time.
CHARGING SUB-SYSTEM			
12	Solar PV Module Performance	PV module power output (Watts)	Measurement of the power output of the solar module for standard test conditions. This is the primary performance indicator of a solar PV module. The performance of crystalline silicon modules can be evaluated with a single test, while the performance of amorphous silicon (thin film) modules must be evaluated over 4-6 months to account for light induced degradation. See Figure 14 for an example.
13	Charging and Battery Storage System Efficiency	%	Ratio of energy input to the charging system (e.g. from a solar PV module or an AC power source) over a charging cycle to the energy delivered to the lamp over a full charge and discharge cycle. This result draws information from tests #5 and #11.
INTEGRATED PERFORMANCE			
14	Application Efficiency	Services/Watt (e.g. Lux-area/Watt)	Ratio of total useful light delivered to the energy input.

* Note: Certain tests may usefully be replicated using a standardized battery with known properties. This would be useful in helping isolate the contributors to performance outcomes.

Table 4. Test Conditions and Equipment.

Individual LED performance

Test conditions
- LEDs powered at 20mA; LED serves as load to determine voltage

Photometry
- LEDs in 4" Photodyne integrating sphere
- LED voltage measured with HP 3456A DMM current with Fluke A90 shunts and HP 3455A DMM (+/- 0.25%)
- Light measured with Tektronix J16 photometer and Licor Photometer (210S)
- Sphere / J16 calibrated with a Sylvania 796 quartz halogen lamp calibrated by Labsphere

Spectral measurements
- LEDs in 4" Photodyne integrating sphere
- Ocean Optics SD2000 spectrometer. Software: OOIBase32, ver. 2.0.6.3, NIST_CQS_Simulation_7.1.xls
- SD2000 calibrated with Ocean Optics LS-1-CAL calibrated lamp to +/- 40K

Illuminance Measurements from Integrated LED Systems

Illuminance distribution on a $1m^2$ surface
- light mounted 1 meter from measurement surface
- illuminance measurements made every 10 cm on a 1 square meter grid
- illuminance: Extech Datalogging Light Meter (model 401036), (precision 0.01 Lux; accuracy +/-3% of reading)

Lamp discharge curve
- light mounted in a "dark box" at a distance of 1 meter from illuminated surface
- light begins test with a full battery; it is discharged completely during test
- illuminance, current from the battery to the light, battery voltage at 1 minute intervals during discharge
- illuminance at center of beam measured with an Extech Datalogging Light Meter (model 401036; see above for specifications)
- current measured with a CR Magnetics DC Current Transducer (model 5210-2) (accuracy +/-1.0%; output signal 0.5 VDC)
- voltage and output signal from current transducer measured with a Hobo H08-006-04 Datalogger (8 bit resolution, accuracy +/-3% of reading)

Tests of Batteries

Battery storage capacity
- measurement made by discharging the battery at a constant current
- discharge curves are collected using a Cadex C7200 series battery analyzer (programmable analyzer; records voltage and current information at 1-minute intervals; 100 – 4,000 mA current range; 1.2 – 16 volts voltage range; NiCd, NiMH, SLA, and Li chemistries supported; +/-1% accuracy)

Tests of Solar Cells

Solar module peak power at standard test conditions
- outdoor performance measurement of module output made on a clear, sunny day
- PV module oriented so that it is normal to sun's beam during test
- peak power estimated from a current-voltage (IV) curve normalized to std. test conditions:1000 W/m^2 and 25°C
- IV measurement collected over 30-40 seconds using a custom data collection system (accuracy +/- 0.5% for current; +/- 0.5% for voltage)
- module temperature measured with Type-K thermocouple (accuracy +/-2%)
- solar insolation measurement made with Licor LI200-SA pyranometer (accuracy +/-5%; LI200-SA calibrated annually with Eppley PSP pyranometer)
- overall accuracy of peak power estimate: +/-10%

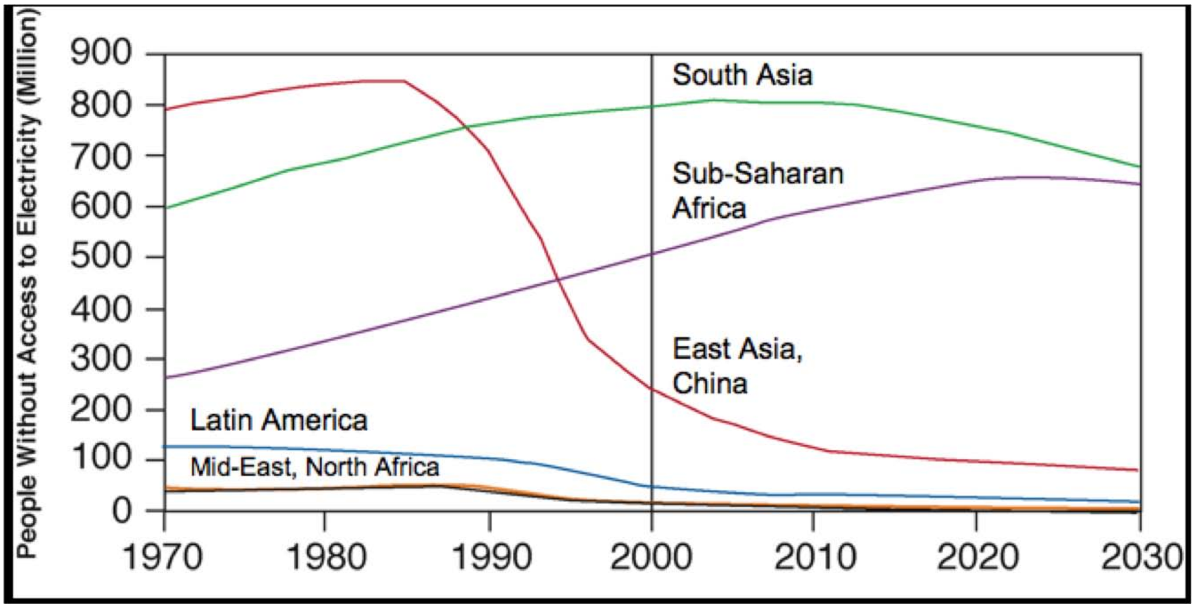


Figure 1. Trends in World Electrification, by Region. Source: International Energy Agency, *World Energy Outlook 2002: Energy & Poverty*

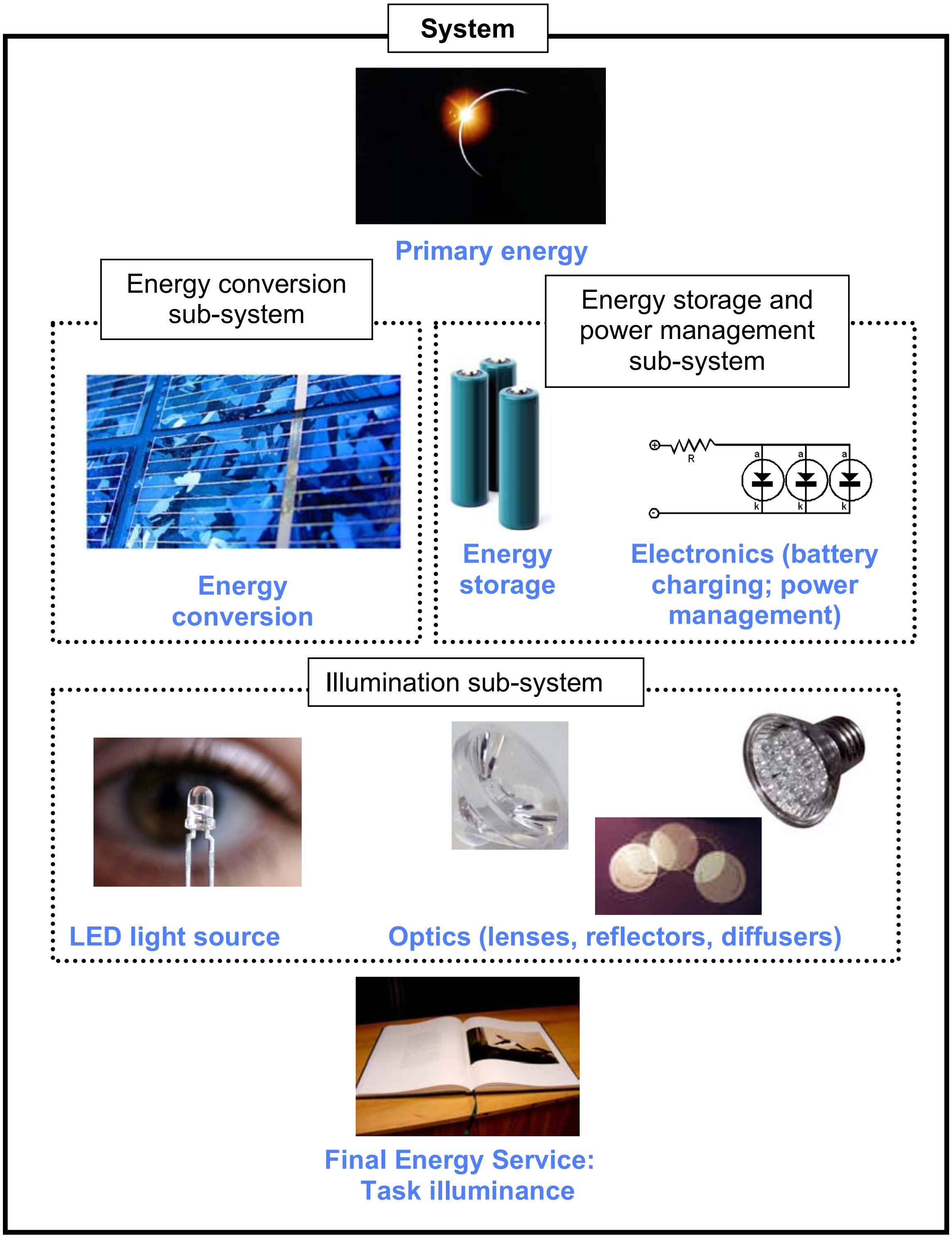


Figure 2. Conceptual Description of an Off-Grid White-LED Lighting System Charged (in this example) Using Solar Electricity. System operation involves the transformation of primary energy into the energy service of illumination. A series of conversions and processes must take place, each entailing some efficiency and thus some losses. The example shown involves direct solar conversion to electricity; other options include grid-based charging and mechanical crank or pump type micro-generators.

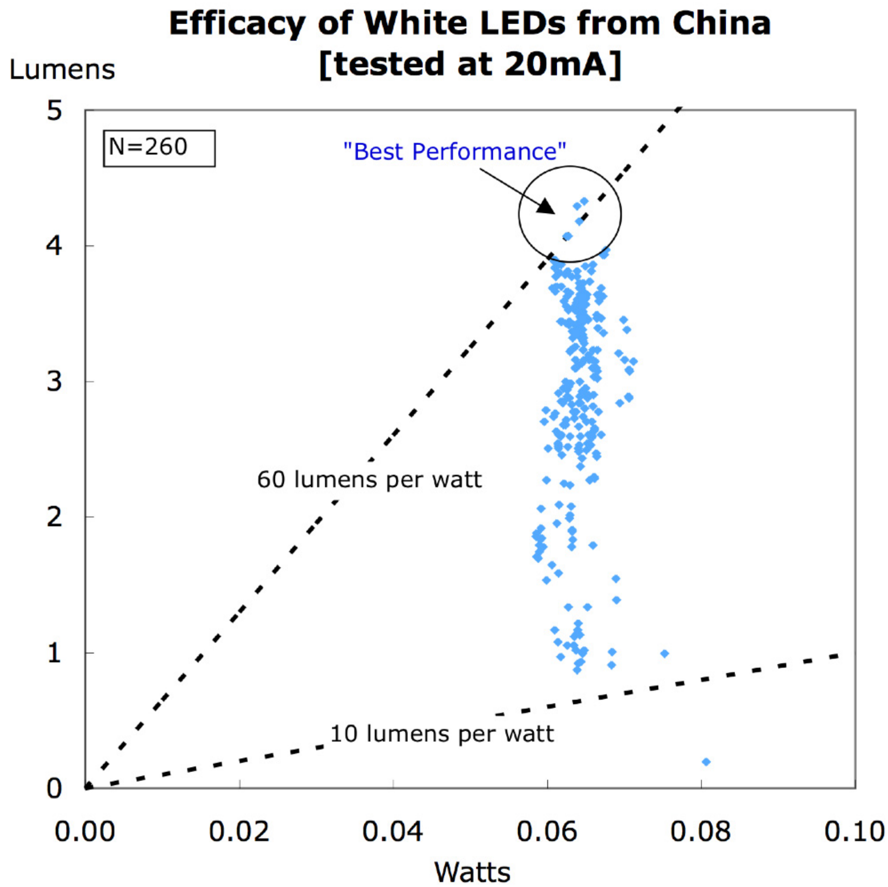


Figure 3. Luminous Efficacy for 26 Batches of White LEDs (260 individual Units, All in the 5mm Size Class). These are individual LEDs, independent of any particular lighting system. For reference, the lower end of this range is representative of typical incandescent lamps while the upper end is representative of the better large compact fluorescent lamps (and considerably better than small, e.g. 3-watt, CFLs which rarely obtain luminous efficacies exceeding 40 lumens per watt).

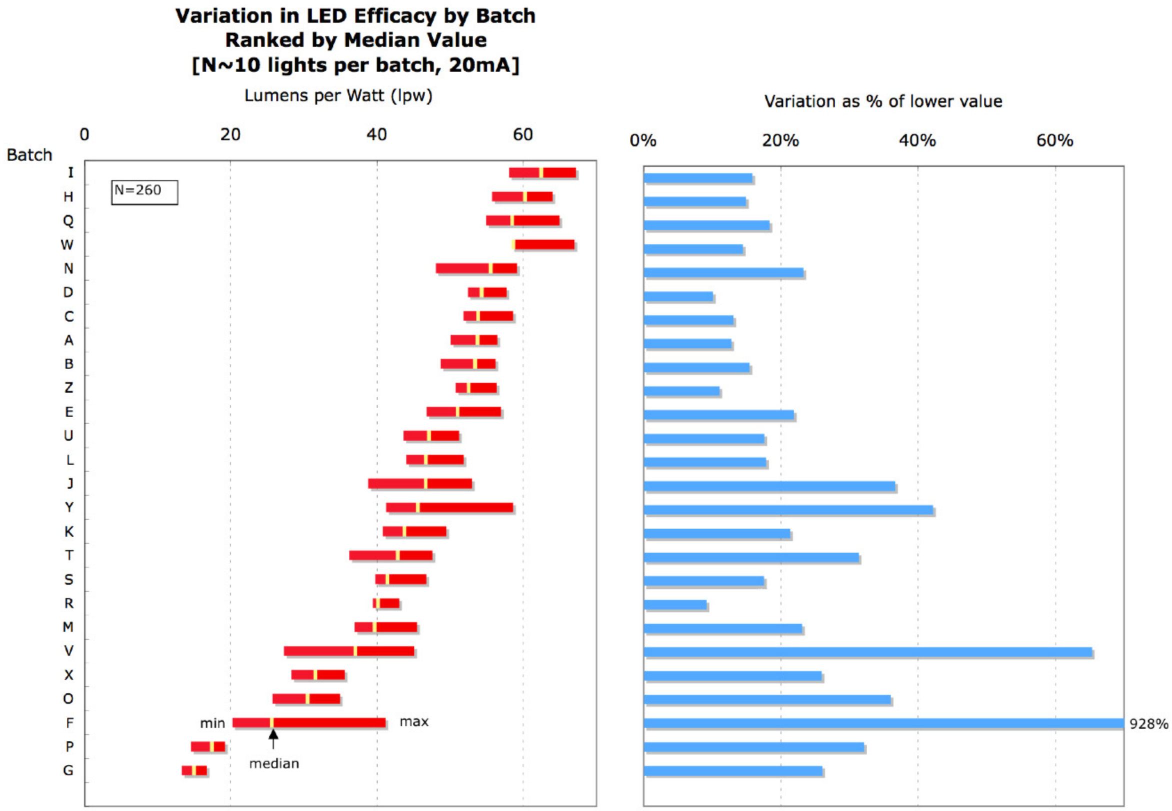


Figure 4. Variation of Luminous Efficacy within 26 Batches of WLEDs.

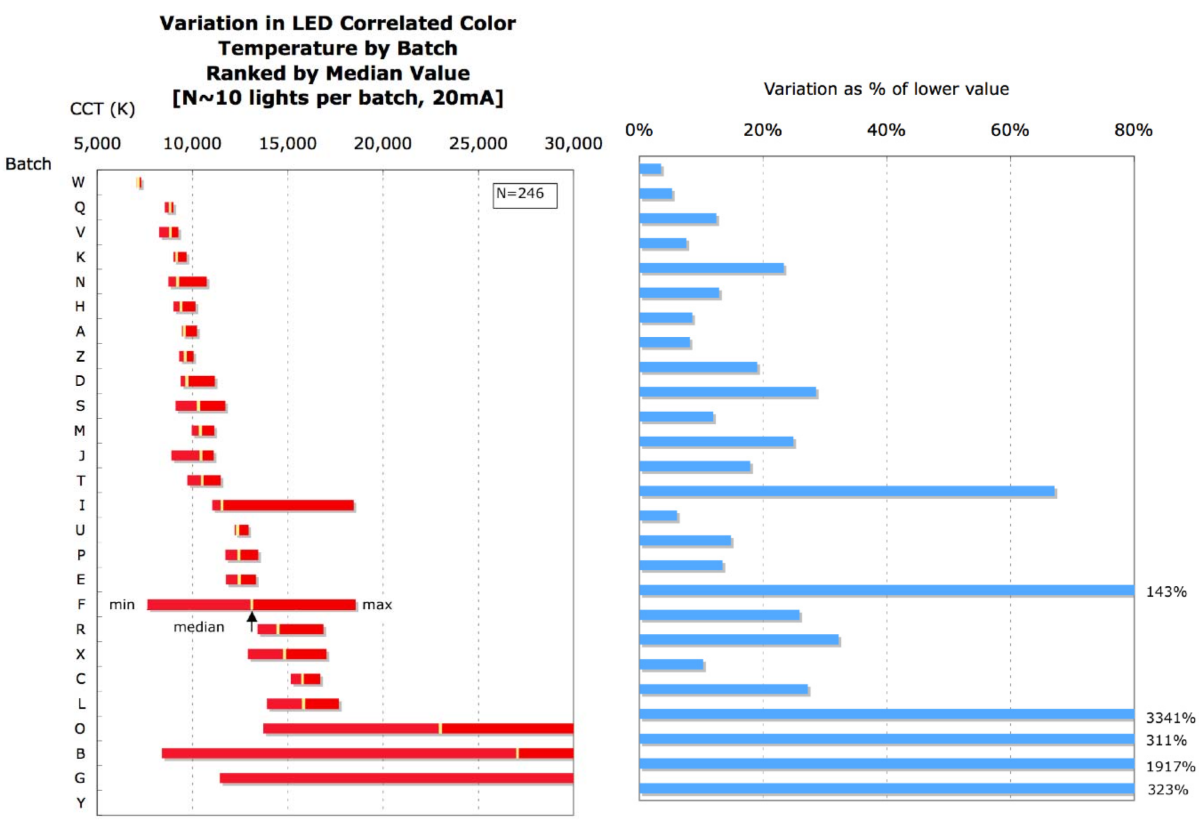


Figure 5. Variation in Correlated Color Temperature (CCT) within 26 Batches of WLEDs.

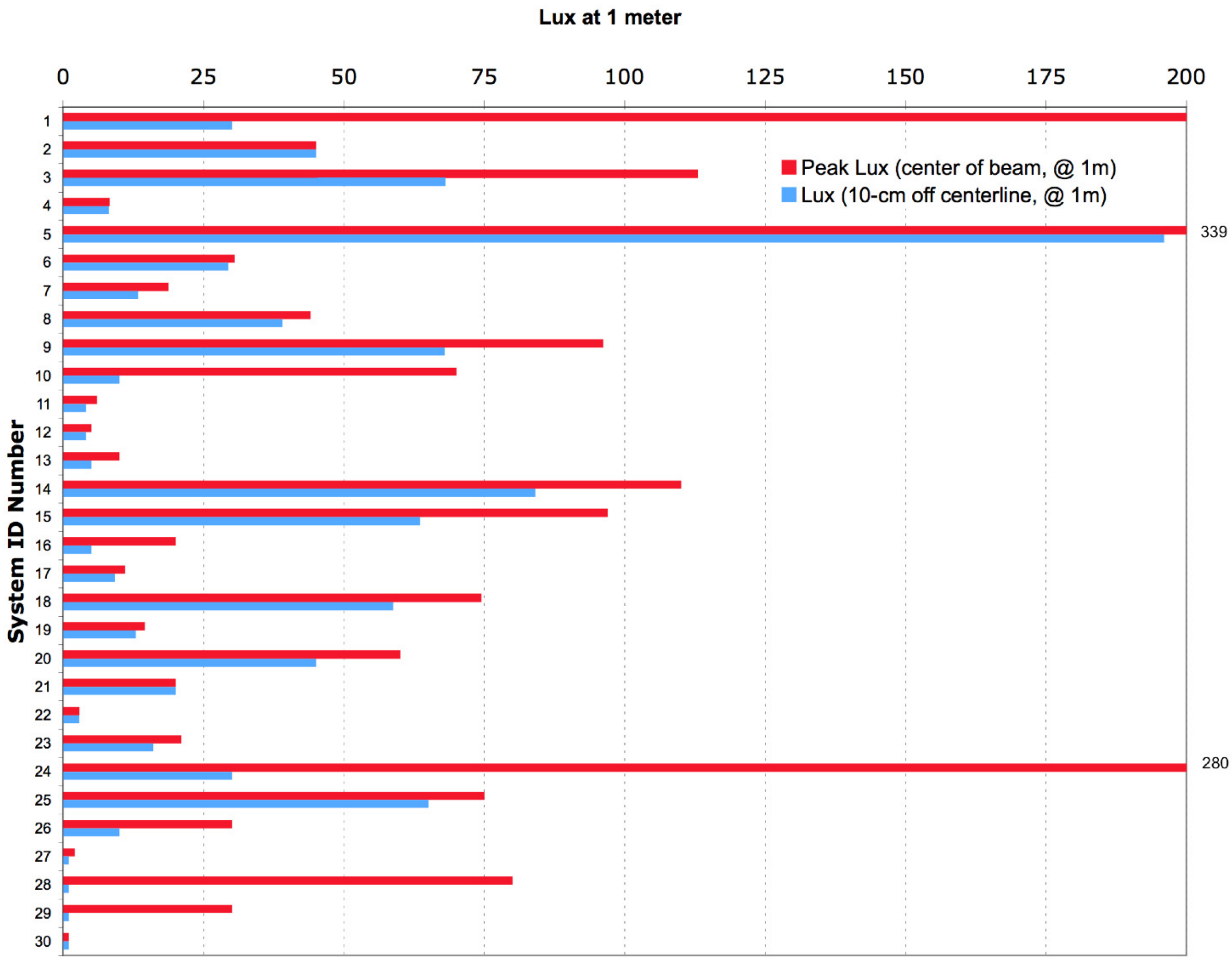
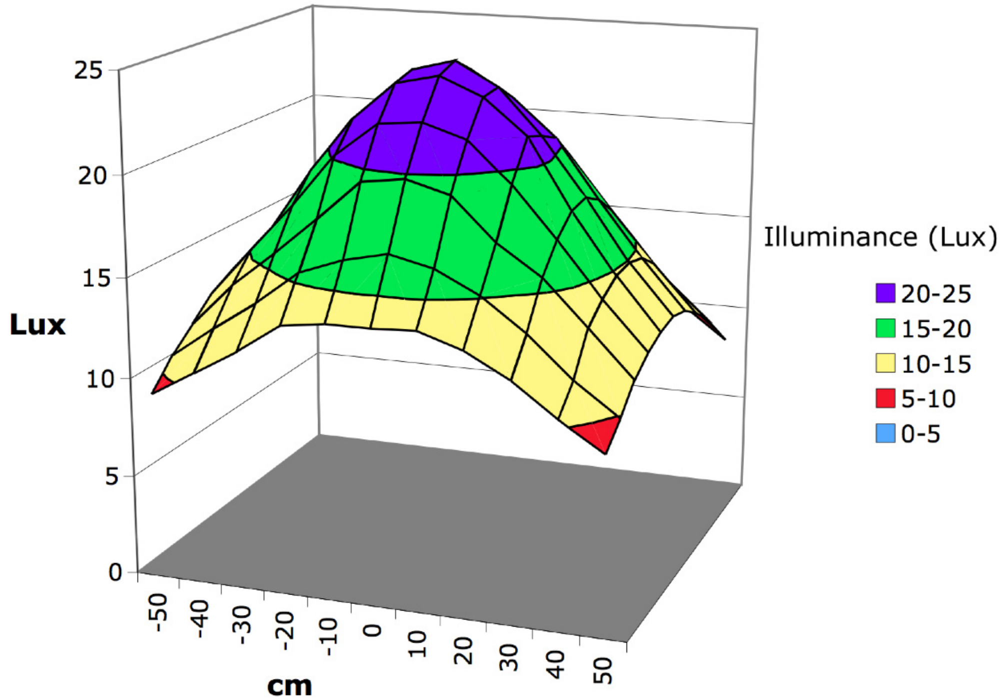


Figure 6. Point Illuminance at a Distance of One Meter for White-LED Systems. The results indicate wide variations in lighting intensity among the lamps. The differences between the measurements at the center-line of the light's "beam" and at a point that is 10 cm from the centerline are related to the optical systems used with each product. Large differences in these two values indicate a focused beam, while small differences indicate relatively uniform light distribution. For reference, the guidelines for illuminance for reading tasks range between 300 and 500 lux in most countries. Many systems depicted in this figure could attain those levels at current distances or if located less than one meter from the task plane.[24]

[24] See Mills, E. and N. Borg. 1999. (*op cit.)*.



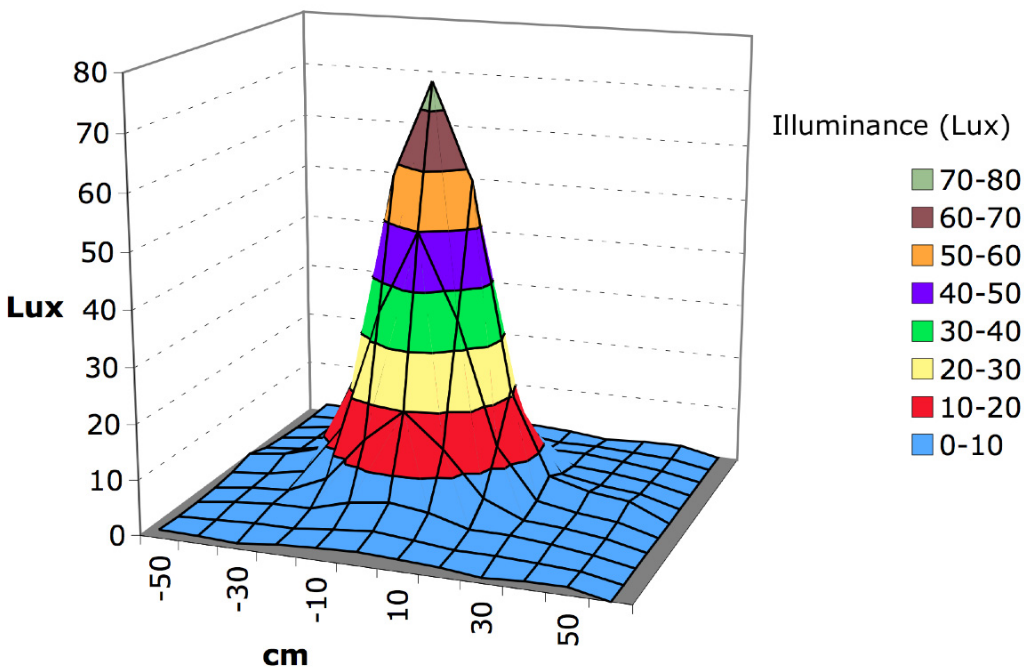


Figure 7. **Illuminance Distribution at a Distance of One Meter for Two White-LED Lighting Systems (System 7, top; System 15, bottom).** While the product on the bottom achieves higher peak illuminance, the product on the top achieves a much greater degree of uniformity, which is important for tasks such as reading.

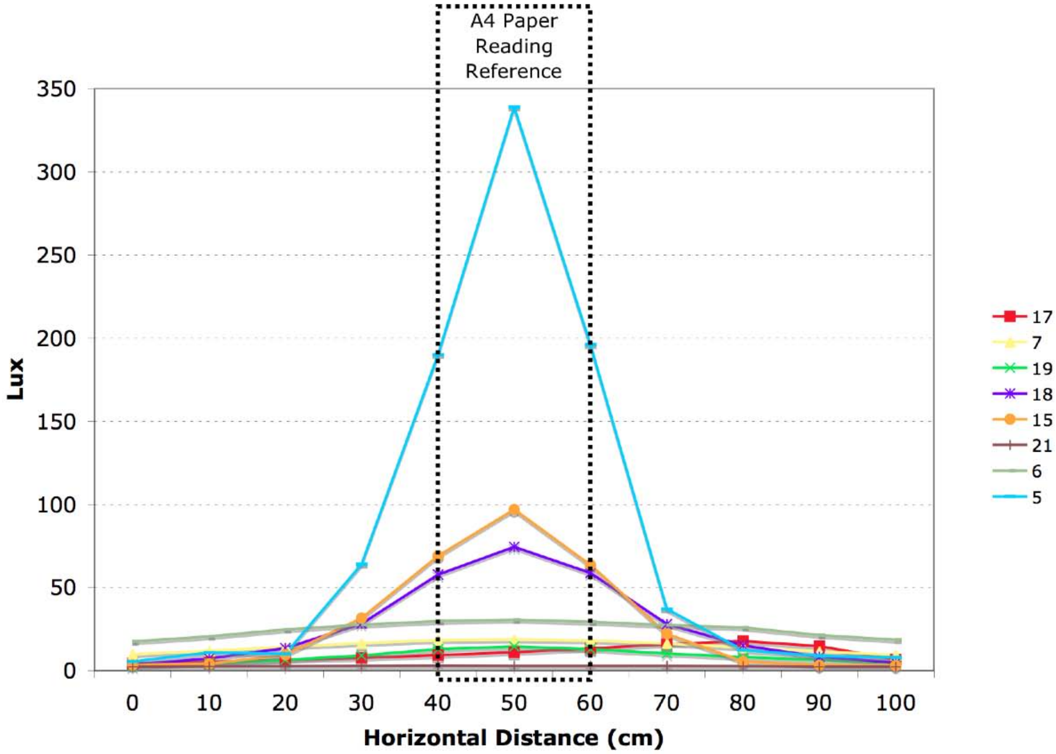


Figure 8. **Illuminance Distribution for Various-LED Systems.** The systems shown exhibit very different lighting levels as well as patterns of illumination. The rectangle delineates the result over an area roughly the size of a book.

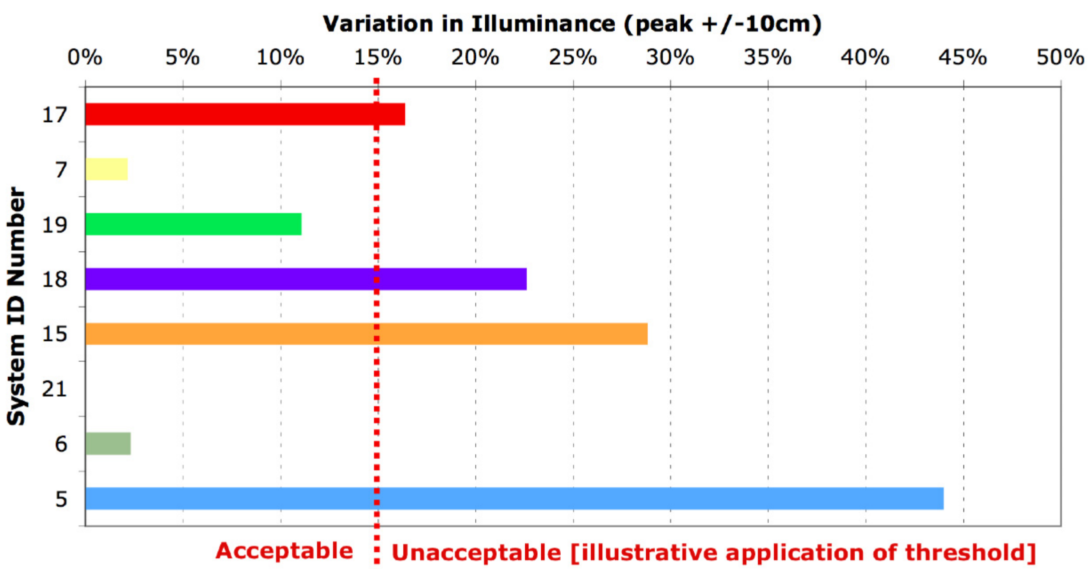


Figure 9. **Illuminance Ratios for Various LED Systems.** The graphic presents the ratio of center-of-beam illuminance to the value at +/- 10 cm for the products shown in Figure 8. The acceptable/unacceptable threshold of +/- 15% over a reading surface is show only for illustrative purposes; defining an appropriate value is somewhat subjective and also dependent on the task.

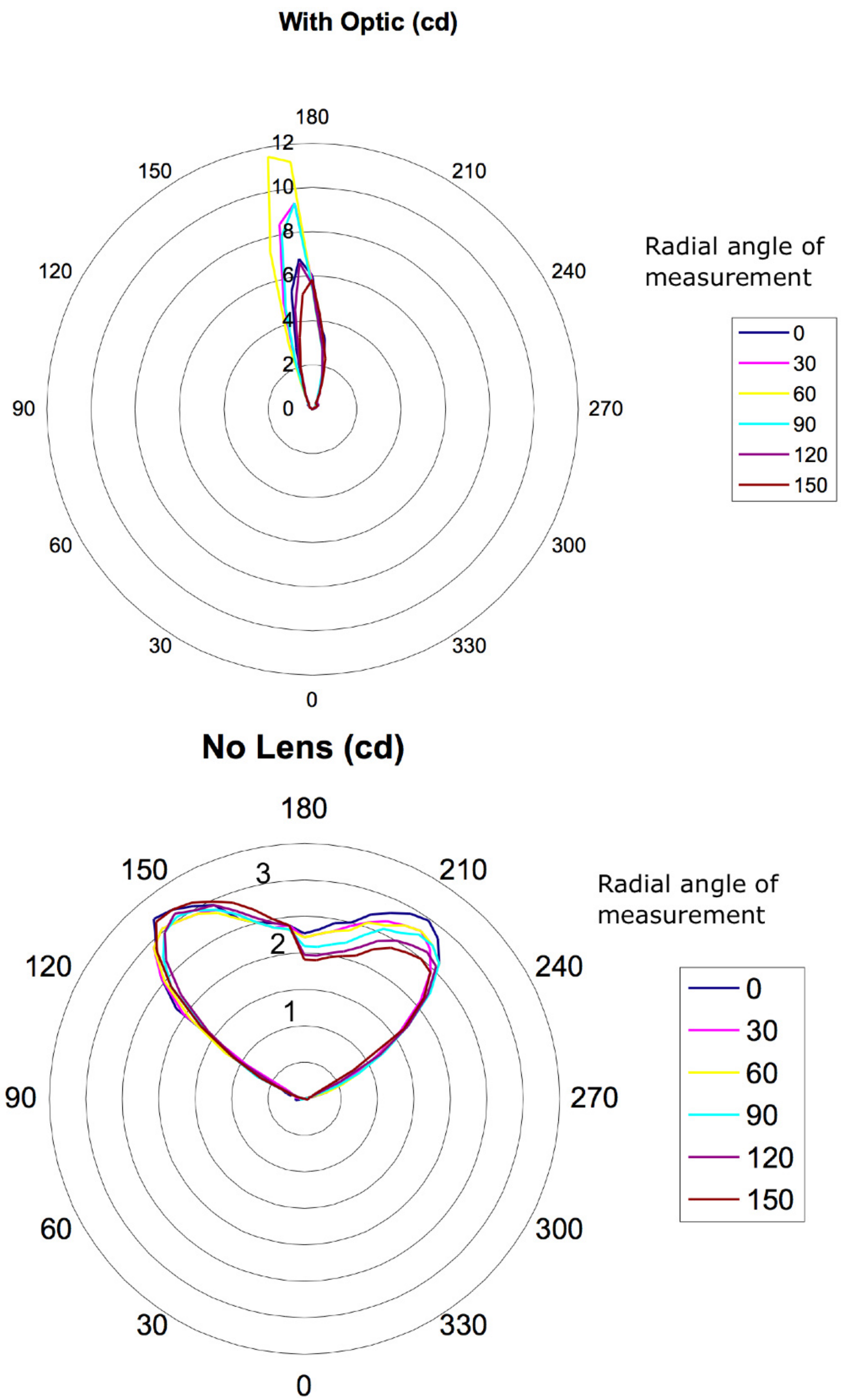


Figure 10. Performance of an WLED Lamp with Optics (System 3, top) and without Optics (System 4, bottom), candelas. The optics produce a columnated beam of light with much higher intensity. Imperfect optics within the LED as well as in the lenses will result in asymmetrical light distribution, which will in turn lead to loss of uniformity of illumination on the task. Were the optics uniform, the radial traces shown in these figures would be coincident.

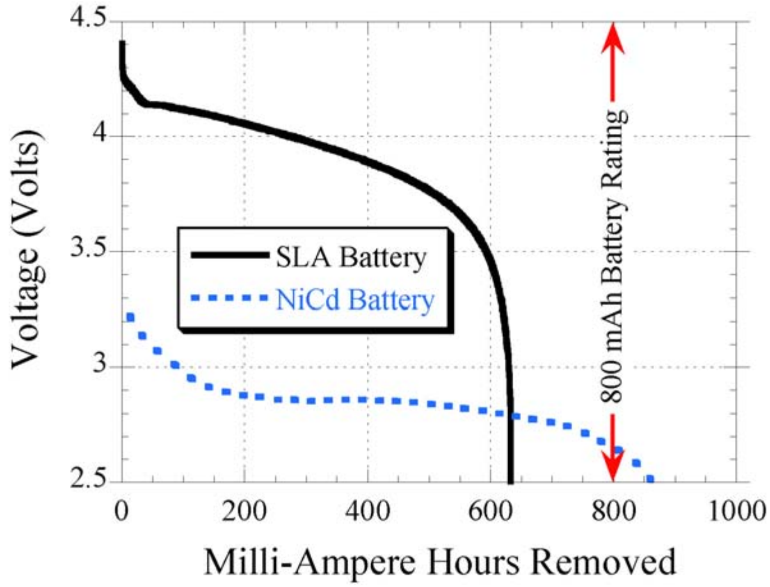


Figure 11. Discharge Curves for an 800 mAh-Rated Sealed Lead Acid (SLA) Battery and an 800 mAh-Rated Nickel Cadmium (NiCd) Battery Pack (System 7 and 15, respectively). The curves indicate that the NiCd battery's performance exceeded its 800-mAh rating, while the SLA battery fell short. The discharge curve for the two cell, 4.0 volt SLA battery was collected at a 20-hour discharge rate. The curve for the three AA-size, 3.6-volt NiCd battery pack was collected at a 1 hour discharge rate. These discharge rates correspond to standard values used by manufacturers to set capacity ratings for the respective battery chemistries.

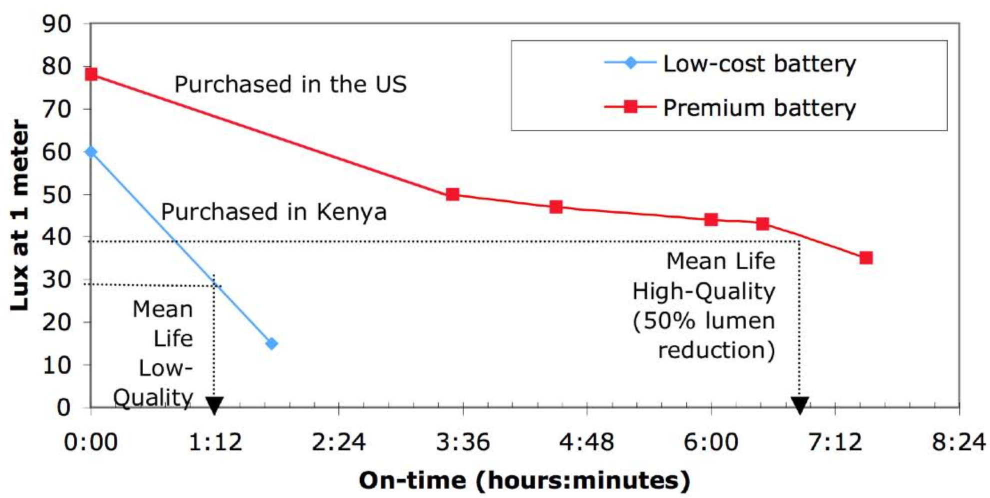


Figure 12. Variability in Alkaline Battery Service Life (System 1, trials with two types of batteries). The low-cost battery (purchased in Kenya) yielded one-eighth as much light at four-times the cost per unit of light.

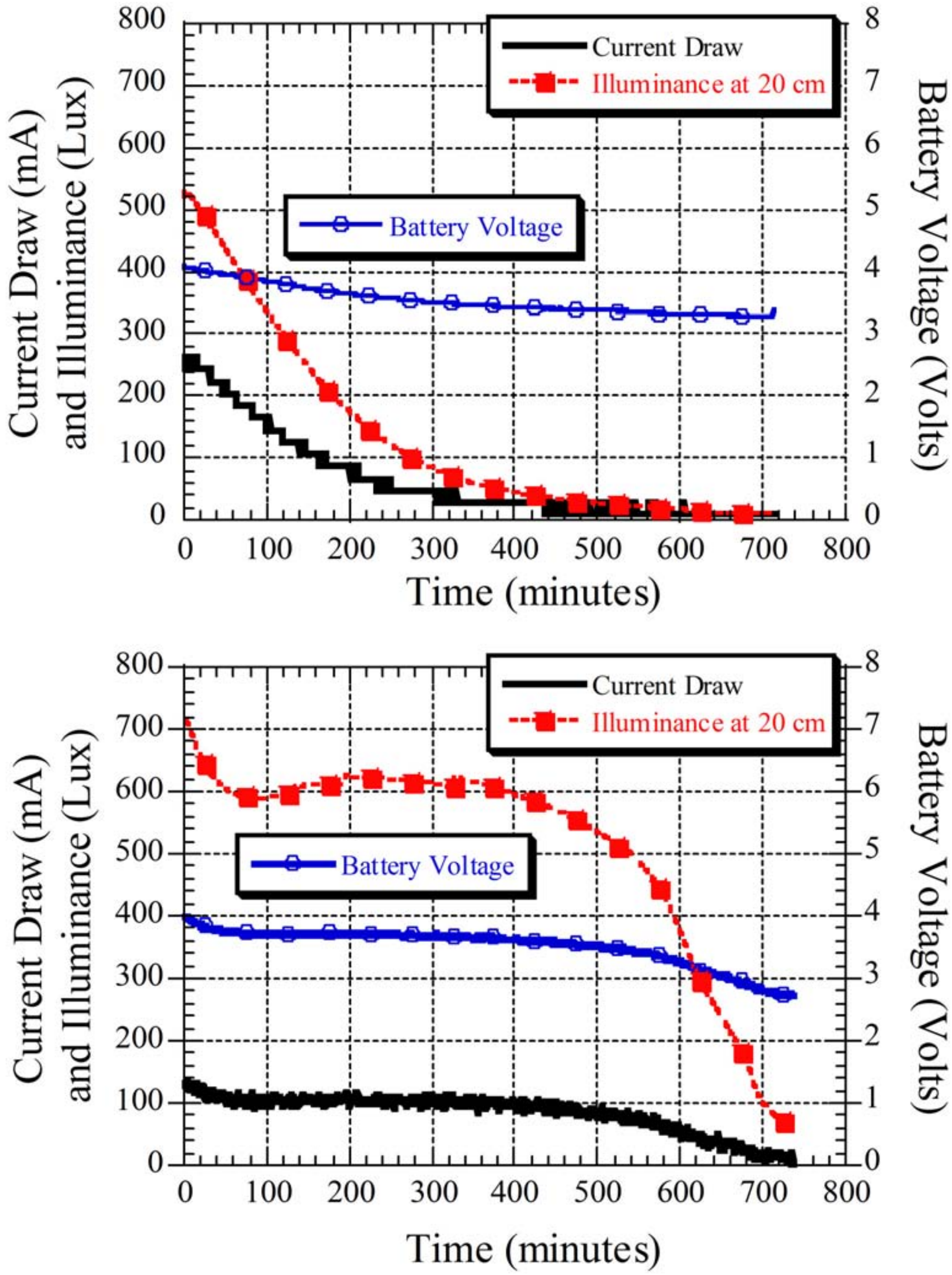


Figure 13. Performance Data for Two Off-Grid White LED Products During Normal Operation (System 7, top; System 15, bottom). The curves include information about battery voltage, load current, and illuminance on a surface for each lamp during a discharge cycle. The upper graphic presents performance data for a product which experiences immediate and significant depreciation of light output (indicating the absence of critical voltage-regulating circuit), while the lower graphic presents data for a product that maintains relatively constant light output over nearly 10 hours of operation. For both trials, the illuminance meter was directly below the light source at a distance of 20 cm.

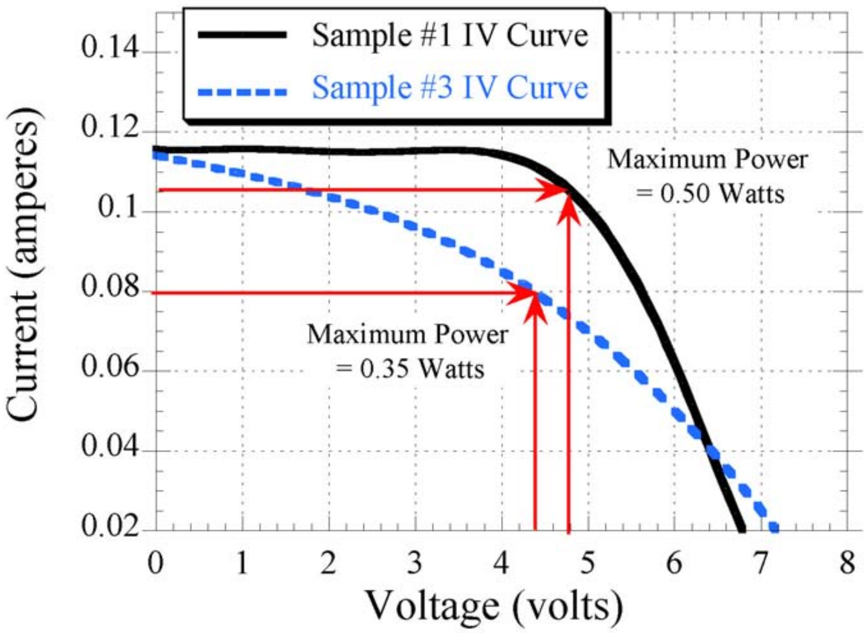


Figure 14. Current-Voltage (IV) Curves for Solar PV Modules Used in a Single Off-Grid WLED Product Line (System 15). The performance of the module in Sample 1 exceeded that of Sample 3 by 30%. The results were normalized to standard test conditions of 1000 W/m^2 and 25ºC.

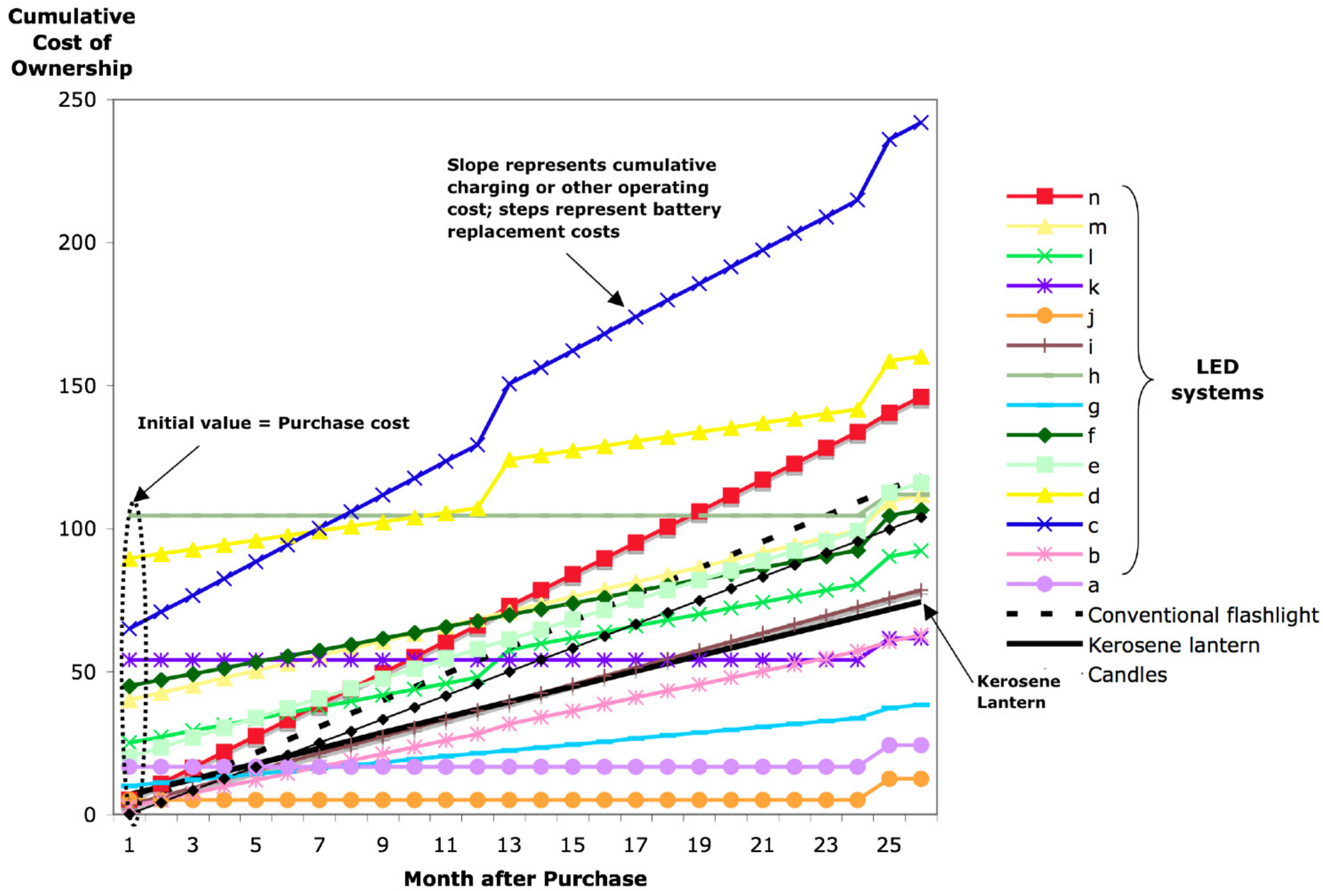


Figure 15. Cumulative cost of ownership for various LED lighting products, with comparison to kerosene lighting and conventional flashlights with disposable batteries. Purchase costs, battery charging, and replacement prices built up based on preliminary analysis of import duties, VAT, and distribution/retail margins representative of the Kenya market. Results are not normalized for the varying levels of service (illumination) provided – kerosene and candles are by far the most costly per unit of useful light. Assumes 3 hours/day operation for all systems. Preliminary economic analysis.

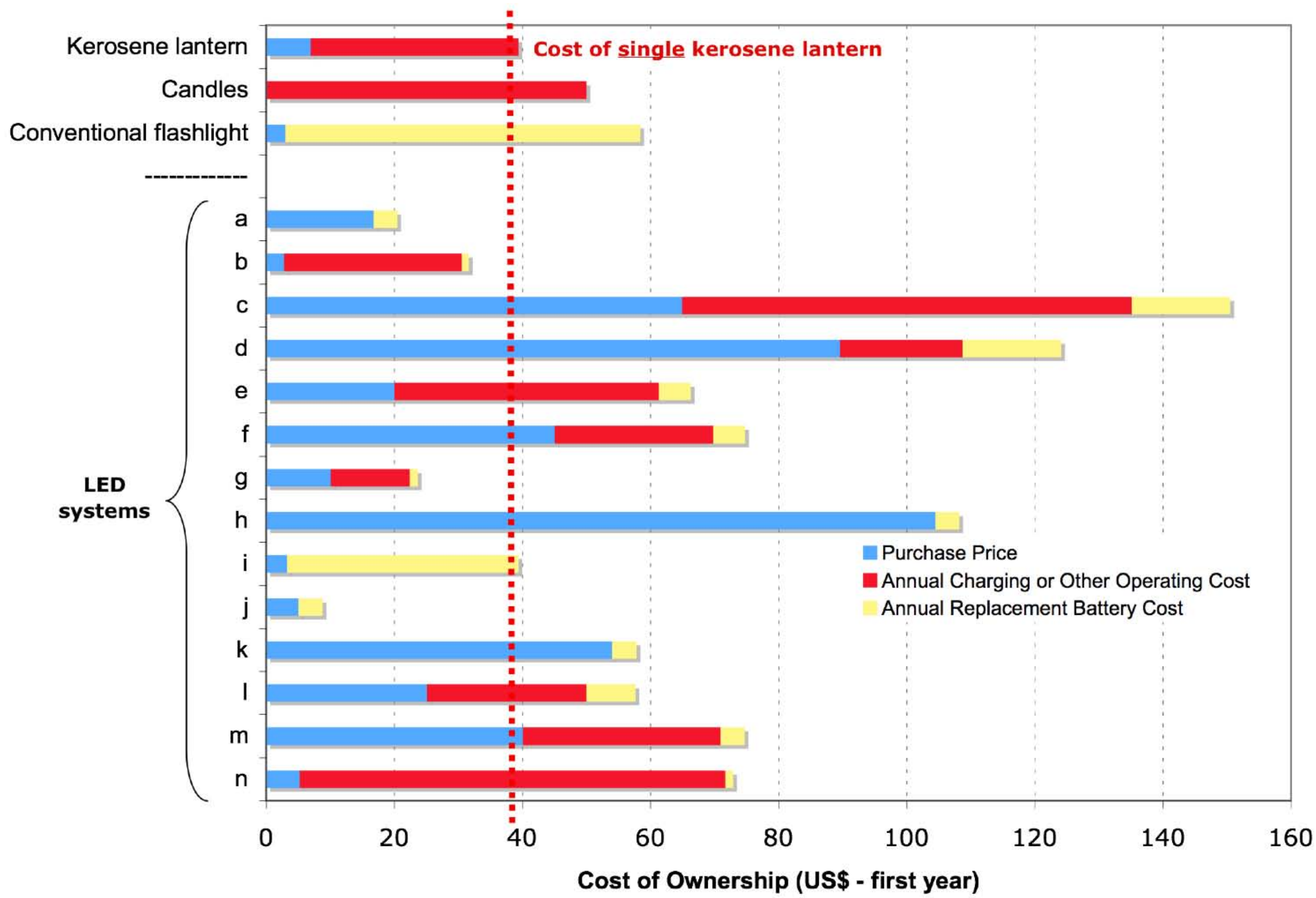


Figure 16. Total yearly cost of ownership for various LED lighting products, with comparison to kerosene lighting and conventional flashlights with disposable batteries. Purchase costs, battery charging, and replacement prices built up based on preliminary analysis of import duties, VAT, and distribution/retail margins representative of the Kenya market. Assumes 3 hours/day operation for all systems. Results are not normalized for the varying levels of service (illumination) provided – kerosene and candles are by far the most costly per unit of useful light.

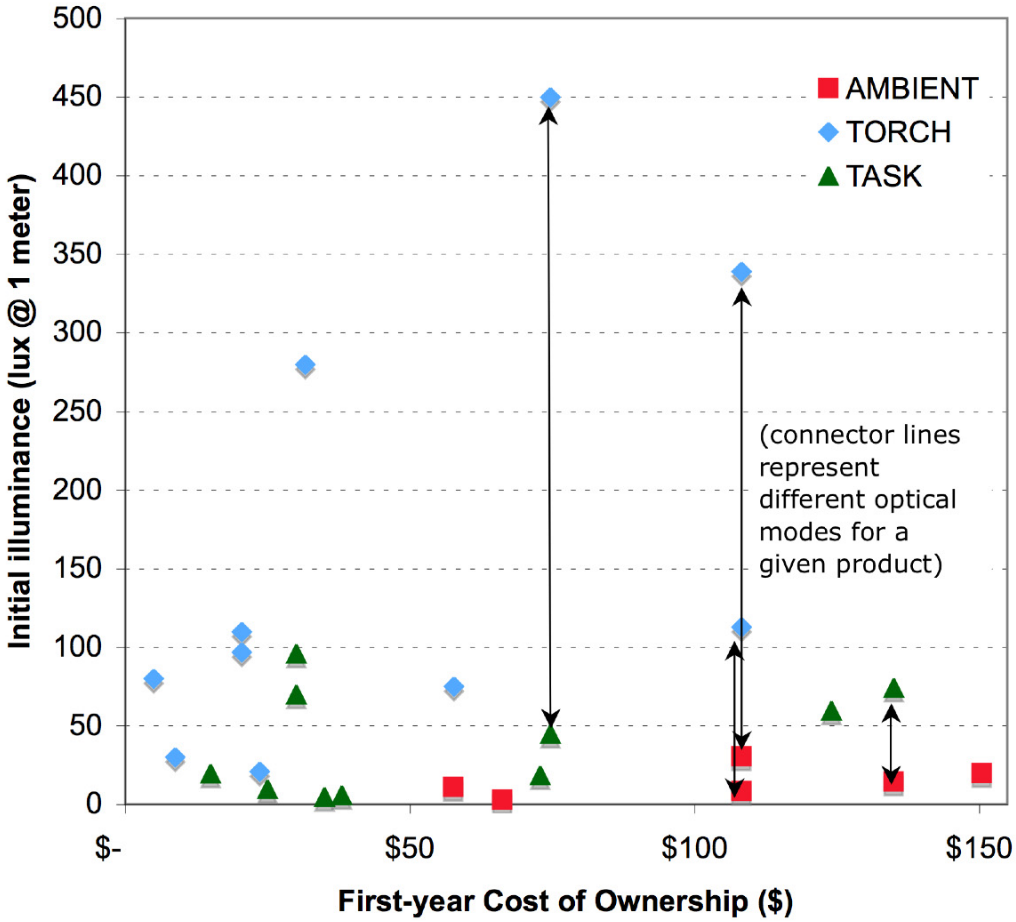


Figure 17. LED system cost of ownership versus lighting service level. The price and performance assumptions for products shown here are identical to those given in Figures 15 and 16, with battery replacement costs annualized. The results also draw from service-level data presented in Figure 6. Arrows show performance points for products with adjustable optics (e.g. wide versus narrow distribution, corresponding to "Ambient" versus "Task" modes of illumination).