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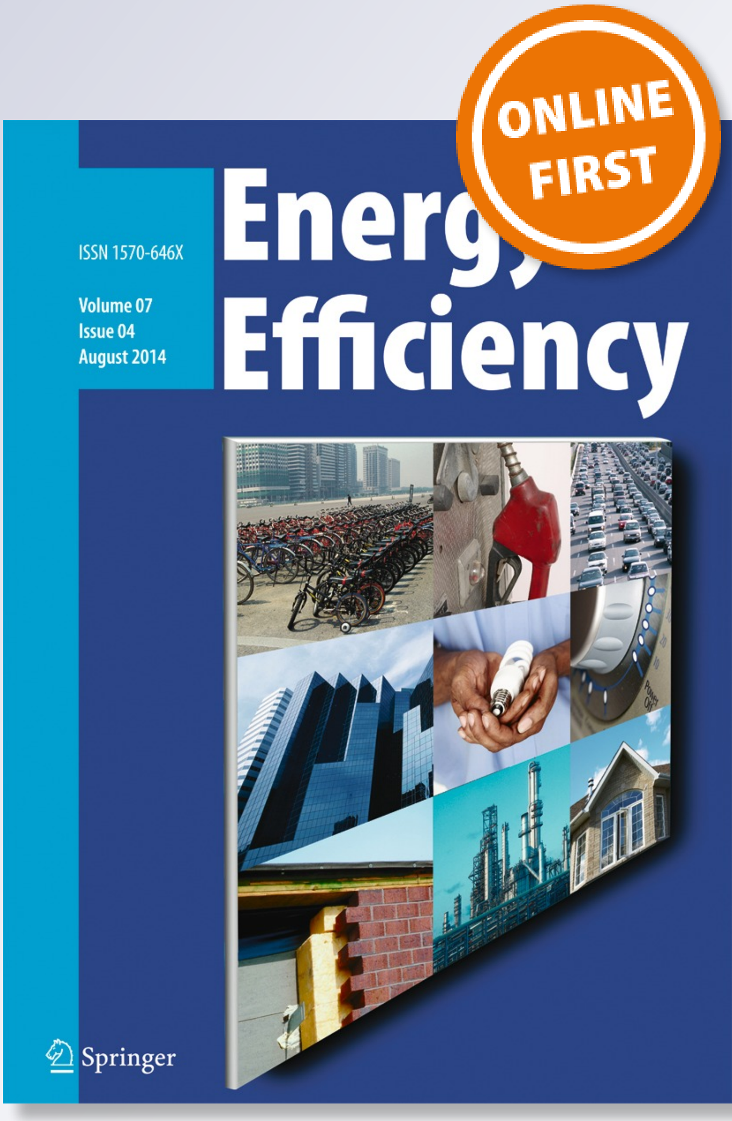

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ORIGINAL ARTICLE

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Abstract Market spoiling stemming from information asymmetry has slowed the adoption grid-independent technologies that replace fuel-based lighting in the developing world. End users typically first experience lighting technology innovations via flashlights. The rapid emergence of inexpensive LED flashlights is a potentially good advancement in this regard, as LED lighting can be longer-lived, have higher initial light output, and be more energy-efficient than incandescent. However, our laboratory tests and end user interviews indicate that these products often fall far short of advertised performance levels and typically fail after a few months of use. Our study of purchasing decisions by 23 Kenyan market traders given an opportunity to purchase warrantied LED lamps found that prior experience with inexpensive LED flashlights significantly reduced their probability of purchasing (p=0.0028). As additional evidence of consumer skepticism, in a large statistical survey, we also find that willingness to pay increases significantly once an LED lighting product is directly handled and tested by the end user. If LED lighting is to achieve its potential as a superior substitute for fuel-based lighting, effective policy measures are needed to remove the information asymmetry between expected and actual performance. One such measure, independent testing and certification, has measurably increased the quality of products available in the off-grid lighting marketplace.

Keywords Quality assurance · Asymmetric information · Energy access · Solid-state lighting · Sub-Saharan Africa

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Introduction and key findings

High-quality yet affordable lighting systems based on emerging light emitting diode (LED) technology have great potential to serve as an affordable substitute for fuel-based lighting (kerosene, diesel, candles, biofuels, etc.) in Sub-Saharan Africa and elsewhere (Mills 2005), but this potential is currently threatened by significant and ongoing market spoiling that stems from information asymmetry.

In this article, which synthesizes several years of laboratory and field research conducted in Kenya, we argue that low-cost LED flashlights have become the dominant handheld lighting technology in many markets, in part because they provide tangible lighting service and economic benefits relative to the incumbent

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flashlight technology. We estimate the national sales of 1 million units per year (Johnstone et al. 2009). Unfortunately, these low-quality LED flashlights are playing a centrally important and overwhelmingly negative role in the development of emerging markets for higher-quality off-grid LED lighting systems (many of which are charged using solar power). The higher-quality systems, which constitute a distinct (but related) market segment, have demonstrated potential to serve as a replacement for fuel-based lighting.

Our previous research on this topic was published largely as narrow-circulation working papers. These earlier reports focused in depth on discrete elements of the issue, e.g., market characterization, product performance, product failure modes, and end user assessments, while this article presents a new synthesis documenting how product quality deficiencies have slowed the adoption of LED lighting technologies. New results are presented from focus groups on consumer information needs as well as policy recommendations, including data on the efficacy of a key policy strategy: independent product testing and certification.

Our work leads to the following key conclusions about the LED flashlights and their connection to emerging markets for affordable, high-quality off-grid lighting systems.

1. Very low-cost imported flashlights using LED technology now dominate the Kenya market, where they have largely replaced the inferior incumbent flashlight technology based on incandescent bulbs and disposable dry cell batteries. LED flashlights that use rechargeable batteries and those that use disposable dry cell batteries are both widely available. Surveys and field observations indicate that LED flashlights have become similarly dominant in a number of other countries in Sub-Saharan Africa.
2. The quality of the low-cost LED flashlights is extremely poor; laboratory measurements of a number of product models and brands available in Kenya indicate multiple and severe performance issues with the LEDs, batteries, electronic circuitry, switches, housings, and other components.
3. End users are very disappointed with the performance of the LED flashlights that they purchase; our survey of end users in Kenya indicates that most low-cost LED flashlights fail within a few months of purchase, thereby significantly increasing lifecycle cost (purchase plus operation) assuming the products are even replaced.
4. Despite their poor performance and short lifetimes, low-cost LED flashlights have achieved fast sales growth because they initially produce more light (i.e., they are brighter) and are less costly to operate than the incumbent incandescent technology.
5. The emergence of low-cost but also low-performance LED flashlights provides a potent recipe for market spoiling in the market for higher-cost, higher-quality off-grid lighting systems that use LED technology, including solar-charged lights for other off-grid applications such as task and room lighting. This is true because low-cost LED flashlights represent many people's first experience with LED lighting technology, and their impressions of the technology can be extrapolated to other LED lighting devices.

This market spoiling dynamic represents a case of information market failure in the sense that many potential buyers of off-grid lighting products are aware of the presence of low-quality products but are unable to distinguish between high- and low-quality goods at the time of purchase. The result is that the sales of good-quality LED lighting products are depressed because some buyers are hesitant to purchase a product that they fear will perform poorly. In such cases, policy interventions aimed at addressing the problem, if implemented effectively, can lead to improved outcomes for buyers as well as for the producers and vendors of good-quality off-grid lighting products.

In the next section, we provide a brief review of literature related to information market failure and its linkage to market spoiling. In the subsequent section, we include background information about the emerging use of LED-based off-grid lighting systems, including low-cost flashlights. This is followed by original analysis and discussion of each of the factors contributing to the market spoiling dynamic outlined above, and real-world evidence of the efficacy of policy interventions.

Information market failure

Market spoiling is an information market failure problem that occurs when potential buyers have difficulty distinguishing between low- and high-quality goods. As described by George Akerlof (1970) in his classic article about used car sales in the USA, the result can be a loss of consumer confidence and a reduction in sales of both low- and high-quality products.

The concept of market spoiling is linked to a line of thinking within economics that is sometimes referred to as New Institutional Economics (NIE). This framework builds on conventional Neo-Classical Economics, highlighting the roles that transactions costs and imperfect (and often asymmetric) information play in shaping economic outcomes (Akerlof 1970; Hodgson 1988; Bardhan 1989; Harriss et al. 1995; Stiglitz 2002). The implication of NIE is that market transactions are often made in the context of imperfect, and often asymmetric, information. When it comes to product purchases, buyers are often uncertain as to whether they have all the information they need to make the best choice. Transactions costs and information asymmetries are broadly present in markets globally, but they can be especially significant in developing country markets that may lack effective institutional arrangements aimed at correcting such market failures (Akerlof 1970; World Bank 1999; Stiglitz 2002).

In situations where a significant number of low-quality products are present in the market and buyers have difficulty distinguishing between high- and low-quality, the resulting market actions can lead to outcomes that are less than the socially optimal level. Duke et al. (2002) provide a detailed analysis of this type of information market failure in the Kenya solar photovoltaic module market during the late 1990s. That analysis notes several types of suboptimal outcomes. First, some buyers suffer direct losses when they purchase low-quality equipment that fails prematurely or performs well below expected levels. Second, as a result of their uncertainty about product quality, some buyers choose not to make a purchase, thereby foregoing what could have been an otherwise beneficial transaction. Elsewhere in the energy sector, similar analyses have been made in relation to information market failure in markets for energy-efficient appliances such as compact fluorescent lamps (CFLs) (e.g., see Birner and Martinot 2005; International Energy Agency 2007).

Duke et al. (2002) note that the vendors of good-quality products (in the case of that analysis, solar PV modules) suffer reduced revenues in at least two ways as a result of this information market failure. First, foregone sales due to buyer uncertainty about product quality lead to a direct loss of revenue. Second, to counteract the uncertainty about the quality of their products, vendors may feel pressure to reduce their prices and/or increase their advertising budgets in order to maintain sales, both of which can lead to a net loss of revenue relative to a scenario where buyers have access to perfect information. The associated losses in sales and revenue lead to reduced profits and, in the case of emerging or otherwise marginal industries, the overall viability of the market may be undermined (World Bank 1999; Duke et al. 2002).

Policy measures to counteract market spoiling typically focus on steps to address information asymmetries (Akerlof 1970; World Bank 1999; Stiglitz 2002). In cases where warranties and/or branding by manufacturers of high-quality products are well established and can effectively be used to signal quality or where strong institutional arrangements such as word-of-mouth information sharing among buyers and potential buyers are likely to emerge organically, direct policy interventions may be unnecessary (Akerlof 1970; World Bank 1999; Duke et al. 2002). In the case that this limited approach is insufficient, voluntary product testing, certification, and labeling programs or other similar interventions aimed at delivering unbiased information to buyers may play a positive role in addressing information asymmetries (Akerlof 1970; Duke et al. 2002; Stiglitz 2002; Ellis et al. 2010). Mandatory standards or even an outright government ban on substandard products are other possibilities, albeit ones that could have net negative outcomes in cases where regulator action is overbearing, ineffective, or corrupt (Duke et al. 2002).

In order to understand how information asymmetries influence the market for solar-charged LED lighting systems for off-grid applications in Kenya, however, it is first necessary to examine some background information about off-grid lighting.

Background

An estimated 1.3 billion people worldwide do not have access to grid electricity (International Energy Agency 2007). In Sub-Saharan Africa alone, nearly 75 % of the population, roughly 550 million people, live in homes without a grid connection (World Energy Outlook 2002; Electricity Access 2009). The overwhelming majority of these people rely heavily on fuel-based lighting from sources such as fossil fuels, candles, and wood fires (Mills 2005). Many more people worldwide have access to unreliable grid electricity characterized by frequent blackouts, and they commonly turn to fuel-based lanterns during outages (World Energy Outlook 2008).

Figure 1 presents the results of surveys indicating the distribution of lighting technologies used on a daily basis among households and market traders in five sub-Saharan countries as of 2008 (Lighting Africa 2010a). Note that ownership rates for lighting technologies exceed the percentages presented in Fig. 1, as many people own lighting devices that they do not use on a daily basis. For example, the same survey indicates that ownership rates for flashlights that are in working order were 16, 15, 27, 25, and 9 % in Ethiopia, Ghana, Kenya, Tanzania, and Zambia, respectively. The percentage with non-working flashlights may be considerably higher. For example, a data set associated with a 2002 report for Kenya indicated 46 % flashlight ownership among households, but this report did not distinguish between working and non-working units (Kamfor 2002). Comparable surveys have not been conducted since 2008.

Fuel-based lighting has a number of disadvantages relative to electric lighting. Most fuel-based lights are dim and the level of lighting service that they offer is very low (Mills 2005). In addition, open flames are a fire hazard (e.g., Oduwole et al. 2003; Dongo et al. 2007) and particulate emissions from fuel-based lamps contribute to indoor air pollution and associated respiratory health problems (Smith and Schare 1995; Apple et al. 2010). Many other health-related risks exist, such as poisonings due to accidental ingestion of kerosene by young children and kerosene explosions due to fuel adulteration with motor fuels (Mills 2012). Fuel-based lighting contributes significantly to greenhouse-gas emissions in the developing world, both as CO_2 and black carbon from wick-based lanterns (Mills 2005). For many of its users, fuel-based lighting is also quite expensive. This is especially true in terms of the cost per unit of lighting service delivered (Mills 2005).

While a very small portion of the un- and underelectrified population newly obtains a reliable grid connection each year, for most reliable power may be decades away. Diesel or renewable energy mini-grids for village electrification provide another alternative, but installation of such systems requires significant investment capital; while the use of mini-grids appears to be growing, they are still relatively rare and typically are installed only in instances where government or donor-based funding is available (e.g., Kirubi et al. 2009; Pighat and van der Plas 2009; Gaul et al. 2010). Moreover, unsubsidized conventional solar home systems (e.g., based on a 15- to 100-W solar module) are cost-prohibitive for much of the population (Jacobson 2007). For these people, relatively low-cost emerging LED lighting systems (e.g., systems that retail for $10 to $100) may offer a superior yet affordable substitute for fuel-based lighting. However, LED lighting's promise depends on the delivery of high-quality products at an affordable price (Mills and Jacobson 2008). While an increasing number of reasonably good-quality LED lighting systems are reaching consumer markets, many perform very poorly (e.g., Johnstone et al. 2009; Mink et al. 2010).

Flashlights are widely used around the world, but they have particular significance for low-income people without regular or reliable access to electric lighting.

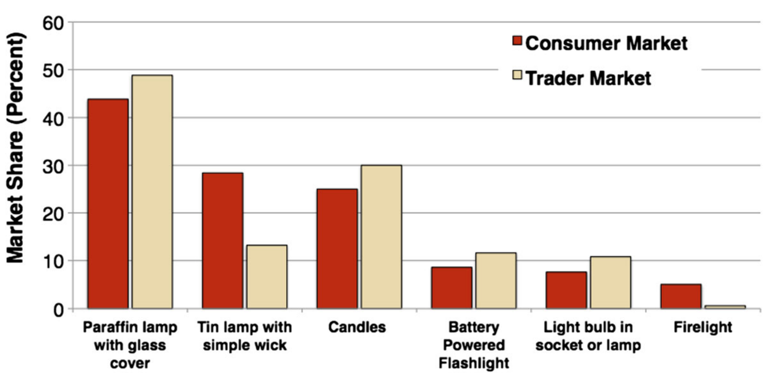


Fig. 1 Types of light sources used on a day to day basis in households ("Consumer Market") and market trading micro-enterprises in five countries. The results show average aggregated response rates for survey respondents in Ethiopia, Ghana, Kenya, Tanzania, and Zambia. The survey sample sizes were as follows: households, Ethiopia (n=1,006), Ghana (n=995), Kenya (n=1,000), Tanzania (n=1,000), Zambia (n=1,000). Market Trader Micro-Enterprises, Ethiopia (n=400), Ghana (n=395), Kenya (n=400), Tanzania (n=400), Zambia (n=396). Figure adapted from Lighting Africa (2010a, b)

Flashlight technology is used for a variety of applications ranging from professional use by security guards to way-finding while walking home at night, among many others. Conventional flashlights have used incandescent bulbs and disposable dry cell batteries for over a century (Eveready 2010), but in recent years LED flashlights have become increasingly common. Well-designed LED flashlights can offer substantially better service than models based on incandescent technology. For comparison, a dry cell battery in a flashlight using the latest commercially available LEDs might last 10–20 times longer than the same battery in an incandescent flashlight. High-quality LEDs in a well-designed flashlight are also considerably more durable, with service lifetimes that can exceed 50,000 h compared to hundreds of hours for a typical incandescent flashlight bulb. In practice, however, as explained below, many LED flashlights perform far below the levels described here.

Market spoiling: analysis and results

In this section, we present analysis and findings building on a series of studies conducted over several years about the relationship between the widespread use of low-quality LED flashlights and hypothesis of market spoiling in the related market segment for solar-charged LED-based off-grid lighting systems. While the analysis draws heavily from research in Kenya, many of the findings have relevance in other Sub-Saharan African countries and other parts of the world. The section is divided into five subsections, which correspond to the five key conclusions outlined in the introductory section above.

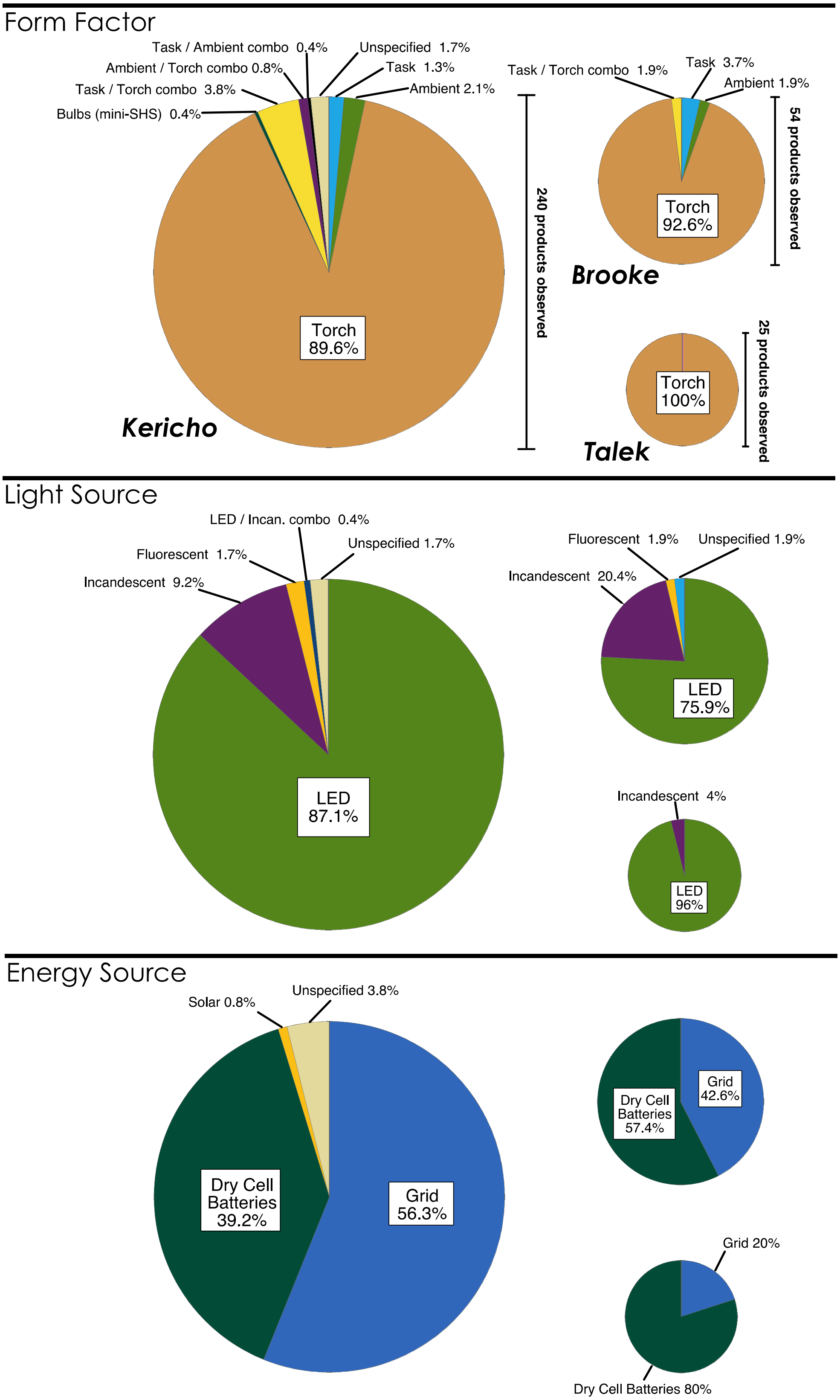
LED flashlights move to dominate markets

The dry cell powered incandescent flashlight has long been a staple energy product in Kenya. A study on household energy use in 2002, before the introduction of LED flashlights to African markets, found that 65 % of Kenyan households reported using a dry cell flashlight (Kamfor 2002). Since then, low-cost LED alternatives have taken over the market in Kenya (Johnstone et al. 2009); anecdotal observations indicate a similar trend in a number of other Sub-Saharan African nations.

In 2009, several of the authors of this article conducted a study on the availability of off-grid electric lighting in three Kenyan towns: Kericho, Brooke, and Talek (Johnstone et al. 2009). Kericho is a large town of 100,000 people in a tea-growing region and Brooke is an outlying market center; there is access to the national electric grid in both towns. Talek is a remote town near Kenya's southern border that does not have grid power. Figure 2 provides a summary of key findings about off-grid lighting products identified in our survey of shops and vendors in those towns. The flashlight (or "torch") form factor is by far the most common type of electric off-grid lighting technology found in the towns, with over 90 % of the products observed having this form factor. As expected, there were a greater variety of form factors available in the largest town, Kericho. Flashlights with LED light sources dominated in each town, and many shopkeepers reported that the incandescent flashlights that remained on their shelves were languishing, as consumers now demand LED technology. LED flashlights come in two varieties: those that have rechargeable batteries and those that are powered with disposable dry cell batteries. We found that the off-grid lighting products in Kericho and Brooke were evenly divided between these two energy storage types, while in Talek dry cells were dominant due to a lack of access to AC electricity for recharging. Anecdotal field observations indicate that the diminishing presence of incandescent, dry cell powered flashlights and their replacement with a combination of rechargeable and dry cell powered LED flashlights, as documented in Johnstone et al. (2009), is also occurring throughout Kenya and in a number of other countries in Sub-Saharan Africa.

The off-grid lighting products that were available in Kericho, Brooke, and Talek had very low retail prices (Johnstone et al. 2009). The median price among the three towns was about $USD 1.75,[1] with very few above $USD 5. Figure 3 shows the distribution in prices observed during the study. The outlier, a $USD 200 solar lighting kit, was available as a complete package in a Kericho hardware store. The solar-charged LED lighting systems that are currently being developed and marketed as alternatives to fuel-based lighting in developing countries and being supported by programs like Lighting Africa are commonly priced five- to ten-or-more-times higher than the median price of the low-

[1] The local currency, Kenya Shillings (Ksh) exchanged at a rate of approximately 75:1 against the US Dollar in summer 2009. This is the exchange rate we use throughout this article, for consistency.


Form Factor
Task / Ambient combo 0.4%
Unspecified 1.7%
Ambient / Torch combo 0.8%
Task 1.3%
Task / Torch combo 3.8%
Ambient 2.1%
Bulbs (mini-SHS) 0.4%
Torch 89.6%
Kericho
240 products observed
Task / Torch combo 1.9%
Task 3.7%
Ambient 1.9%
Torch 92.6%
Brooke
54 products observed
Torch 100%
Talek
25 products observed
Light Source
LED / Incan. combo 0.4%
Unspecified 1.7%
Fluorescent 1.7%
Incandescent 9.2%
LED 87.1%
Fluorescent 1.9%
Unspecified 1.9%
Incandescent 20.4%
LED 75.9%
Incandescent 4%
LED 96%
Energy Source
Unspecified 3.8%
Solar 0.8%
Dry Cell Batteries 39.2%
Grid 56.3%
Dry Cell Batteries 57.4%
Grid 42.6%
Grid 20%
Dry Cell Batteries 80%

◀ **Fig. 2** Characterization of the off-grid lighting products available in the Kenyan towns of Kericho, Brooke, and Talek in June 2009. The pie charts are proportional in size to the quantity of products available. Adapted from Johnstone et al. (2009)

cost products that we observed in summer 2009. For example, the five products that won Lighting Africa Outstanding Product Awards in May 2010 cost between $20 and $100 in African retail markets.[2] Consumer expectations of price and quality are thus being shaped by the low-cost products that are currently available, which can pose roadblocks to higher priced, higher-quality LED lighting systems that enter the market (Mink et al. 2010; Tracy et al. 2009). In the next section, we summarize results from our laboratory testing of commonly available LED flashlights purchased from retail vendors in Kenya.

Poor performance of low-cost LED flashlights

A variety of commonly available flashlights were purchased from retail outlets in Kenya in 2008 and 2009 to evaluate the performance of low-cost LED flashlights (Tracy et al. 2010b; Mink et al. 2010) using standardized laboratory testing protocols (Lighting Africa 2009).[3] The results confirm very low performance across a number of metrics; they also show that manufacturer claims often grossly exceed actual performance.

From a consumer perspective, three key areas of LED flashlight performance are centrally important: light output, the duration of lighting from a full charge or set of fresh batteries, and the durability of the product. In this section, we provide a summary of performance results in these three areas for a variety of flashlights commonly available in Kenya.

Many consumers prefer LED flashlights because they tend to produce more light (i.e., they are brighter) than similarly priced incandescent flashlights. However, the initial light output of the LED flashlights we tested degraded very quickly (Mink et al. 2010) (incandescent light sources are not subject to significant degradation). Figure 4 shows the initial light output of 10 different flashlight products tested by Mink et al. (2010) and the lumen maintenance of the flashlights in terms of the industry-standard “L70” lifetime, i.e., the duration of time in hours before the light output reaches 70 % of the initial level, a common way of specifying lumen maintenance (Lighting Africa 2010b). Tests were conducted on six identical units of each of the 10 flashlight products. The flashlights that were tested were purchased from a number of retail outlets in several different Kenyan towns. The results presented in Fig. 4a show that the low-cost LED flashlights that we tested delivered much more light initially than most commonly available incandescent flashlights, although output varied by a factor of four across products. However, as shown in Fig. 4b, the LED units degraded to 70 % of their initial light output after between 10 and 150 h of operation and to below 20 % of initial light output after 100 to 500 h (Mink et al. 2010). The L70 performance corresponds to a matter of weeks or months of calendar time at typical use rates; this is orders of magnitude shorter than claims commonly made on packaging of LED products sold in many African markets (including Kenya), which often tout LED lifetimes on the order of 50,000 or 100,000 h.

For the many users who either pay a fixed price to recharge their flashlights at a charging business or purchase dry cell batteries, the duration of lighting service determines the operating cost of the flashlight (see “LED flashlight sales likely to grow due to favorable economics” section for more discussion of the economics of flashlight use). Our laboratory testing showed that the duration of operational time was vastly overstated on

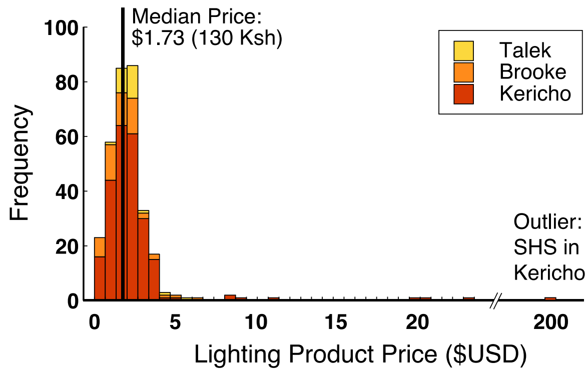


Fig. 3 Distribution in the prices of off-grid lighting products observed for sale in July 2009 in the Kenyan towns of Kericho, Brooke, and Talek. Adapted from Johnstone et al. (2009). Solar home systems are abbreviated as SHS in the figure

[2] See http://www.lightingafrica.org/node/109966 for additional information about the Lighting Africa Outstanding Product Awards competition.

[3] Initial research and work in developing some of these test procedures was conducted under the Lumina Project (Mills and Jacobson 2008; Granderson et al. 2008). Tests conducted by the Fraunhofer Institute for Solar Energy Systems (FISE) for GTZ also provided an important foundation for the methods that were subsequently expanded and refined by FISE on behalf of Lighting Africa.

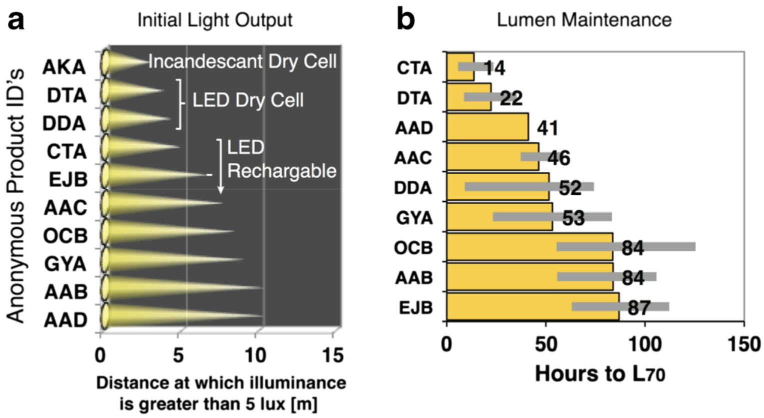


Fig. 4 **a** The initial light output of flashlights in terms of their functional distance (i.e., distance at which they deliver >5 lx of illuminance to a surface) and **b** the lumen maintenance of LED flashlights measured by hours to reach "L70" (i.e., 70 % of initial light output). The anonymous product codes were developed for the original publication. The *gray bars* on plot B are the minimum and maximum observed L70 lifetimes for each product. n=6 for each product tested, indicating a lower degree of consistency in performance among ostensibly identical products. Note that the order of the products is different in each graph. Both are adapted from Mink et al. (2010)

the packaging (Fig. 5). Among the rechargeable LED flashlights, the measured run time ranged from 10 to 40 % of the advertised time (Mink et al. 2010). In part, the low run times are due to poorly specified and managed batteries. The batteries in low-cost rechargeable LED flashlights are overspecified (i.e., their rated battery capacity exceeds their measured capacity) and are unprotected from over- and undercharging, meaning that they underperform from the start and have a shortened lifetime due to the harsh treatment that they receive in terms of over- and undercharging (Mink et al. 2010). The specified battery capacity on seven LED flashlights, all of which had sealed lead acid (SLA) type batteries, ranged from 600 to 1,300 mAh, but the measured battery capacities were much lower, between 30 and 40 % of the ratings. In addition or as an alternative to being poorly specified, the initial capacities may be reduced due to time spent in the supply chain prior to purchase. Members of our team observed many products available for retail sale that had been manufactured more than 1 year earlier. Sealed lead acid batteries can be damaged permanently if they stay at a low state of charge for an extended period of time; additionally, SLAs slowly lose their charge over time through a process known as self-discharge (Linden and Reddy 2001). Batteries that remain in the supply chain for an extended period without being charged are therefore deeply discharged long before purchase. The long period between manufacture and retail purchase may, therefore, have contributed to the low measured battery capacities. Moreover, some

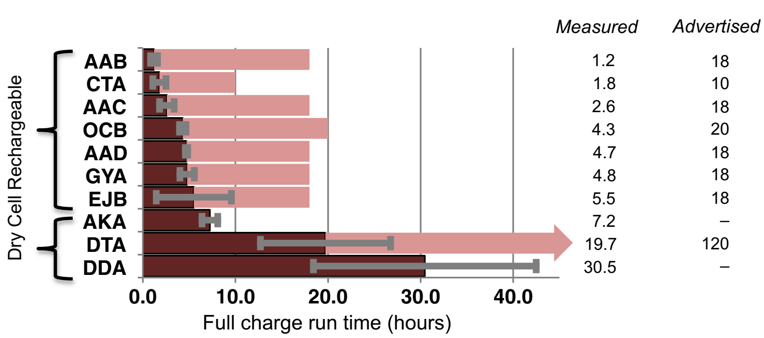


Fig. 5 Duration of operational time per full charge for flashlights from the 2009 Kenya market (n=6 for each product). The average measured time for each product is shown with 95 % confidence intervals (*darker bar shading*) along with the advertised run time (*lighter bar shading*). Note that there was no advertised run time for two of the products (AKA and DDA). Adapted from Mink et al. (2010)

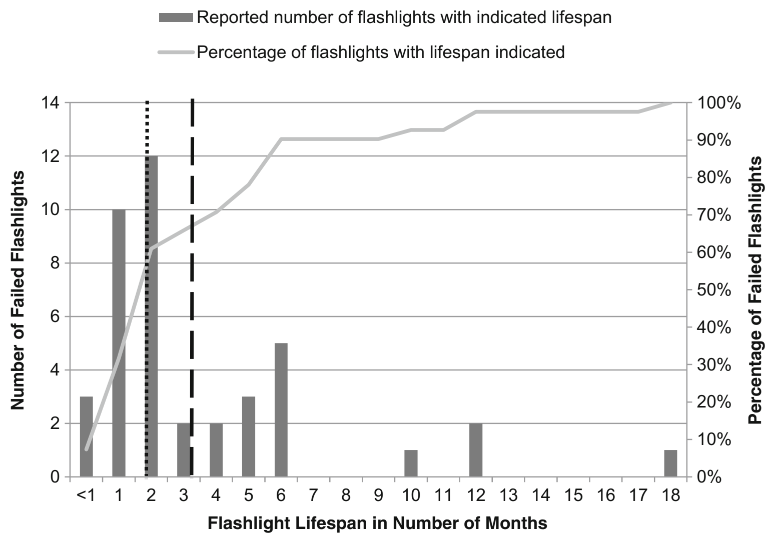


Fig. 6 The *bar graph* indicates the number of flashlights in each lifespan bin as reported by participants (primary *y*-axis). The dotted line represents the median flashlight lifespan and the dashed line represents the mean average reported lifespan. Cumulative probability plot of flashlight lifespan as reported by study participants (light gray line, n= 41, secondary *y*-axis) (Tracy 2010)

flashlights that we observed had been switched on inadvertently during shipping, which further exacerbated the deep discharge problem (Johnstone et al. 2009).

The lack of deep discharge protection circuitry means that the capacity is further reduced each time a consumer fully discharges the battery. This can be avoided if users refrain from discharging the battery fully, but most products do not include an indicator of battery state of charge other than the relative brightness of the light (i.e., the light output from the flashlight dims as the battery discharges). Additionally, the low-cost rechargeable LED flashlights we have observed universally use a simple rectifier circuit to control the battery charging process. The rectifier circuits will allow the batteries to be overcharged if they are left to charge for the amount of time specified on the packaging, causing drastic reductions in the cycle life (Mink et al. 2010).

Overall durability will determine the lifetime of the product and how often it must be replaced. In the lab testing by Mink et al. (2010), we found that a combination of failure mechanisms led to expected flashlight lifetimes on the order of months. Mechanical and electrical failures from breakage and water intrusion are frequently related to the use of brittle plastic housings, poor quality of solder joints and other electrical connections, and the presence of large openings in the housings which allow for water and dust entry. These factors, combined with typical-use patterns of flashlights, which are inherently mobile devices that are handled and sometimes dropped during operation, lead to frequent and early breakage (Tracy et al. 2009; 2010b). The LED arrays can be severely damaged instantly in some recharging scenarios[4] and degrade quickly in normal operation (see Fig. 4b). Finally, as discussed above, the batteries are not protected from deep discharge during shipping and distribution or operation, leading to failure either before the product is sold or after as few as dozens of charge/discharge cycles (Mink et al. 2010).

All of these problems have led to high levels of consumer dissatisfaction. Lighting Global (incorporating the Lighting Africa and Lighting Asia/India programs) has established a quality assurance test protocol that examines many of the aforementioned causes of performance degradation and product failure (see http://lightingglobal.org). However, most flashlights sold in the developing world have not been submitted for Lighting Global's review.

Retailer and end user dissatisfaction with LED lights

LED flashlights have the potential to provide high-quality lighting services for these important applications, but the poor quality of the low-cost products that are widely available has led to serious levels of dissatisfaction.

Our research in Kenya documenting the experiences of low-income frequent users of LED flashlights indicated that within a 6-month period 87 % of the 41 end

[4] If the switch is in the "on" position when a rechargeable LED flashlight is plugged into the wall, a brief voltage spike can damage individual LEDs or the entire LED array (Mink et al. 2010).

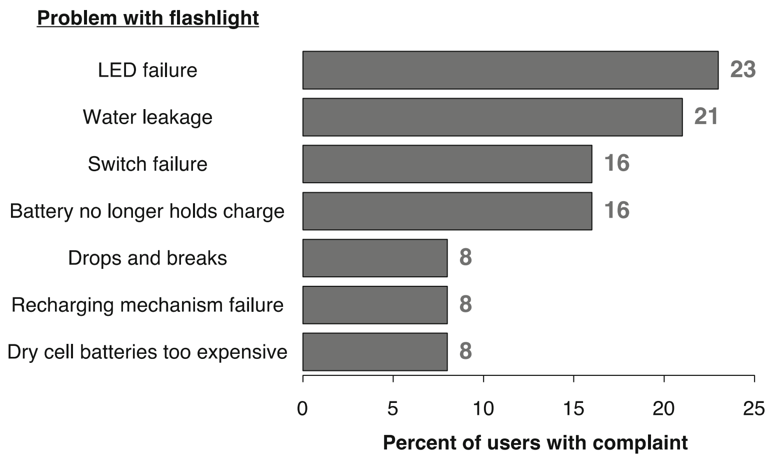


Fig. 7 Summary of common problems experienced by 46 flashlight users surveyed in Kenya. Four problems make up 75 % of the reported complaints. These include LED failure, water leakage, reduced battery capacity (i.e., battery no longer keeps the charge), and switch/wiring failures (Tracy et al. 2009; Tracy 2010)

users surveyed reported having problems with their flashlights, and the median reported lifespan was 2 months (Tracy et al. 2009; Tracy 2010) (Fig. 6). This short lifespan, with flashlight use patterns that ranged from 20 min to just under 4 h per day, is consistent with the predictions of LED flashlight lifetime based on laboratory results of their performance and durability reported in Mink et al. (2010). In the context of our field survey of flashlight users, LED failure was the most commonly cited failure mode. While the cause of the problem may or may not have been related to actual failure of the diode itself, the end users interviewed in this study appeared to interpret the fault as a problem with the LED (Tracy et al. 2009; Tracy 2010). In addition to LED failure, six other types of complaints were also reported with frequency (Fig. 7). Further corroborating this concern, those who sell flashlights repeatedly note that customers are dissatisfied with the quality of the available products, and that there is not a reliable source of information about product quality (Johnstone et al. 2009). Of the 60 shopkeepers we surveyed, 41 (68 %) reported problems with product quality.

These results strongly suggest severe and widespread quality problems in the Kenyan LED flashlight market. In fact, descriptions of flashlight failure modes suggest that LEDs commonly ceased delivering light after only a few hundred hours of operation (Tracy 2010; Mink et al. 2010). This is particularly worrisome given, as noted above, that many manufacturers market the flashlights with claims that the LEDs will last a very long time compared to incandescent bulbs.

Table 1 Annual cost of ownership for three common flashlights used in Kenya

Flashlight type	Annual cost of ownership (USD)	
	With charging fee	Without charging fee (e.g., solar)[a]
LED rechargeable	\$38	\$12
LED dry cell	\$22	NA
Incandescent dry cell	\$43	NA

Annual cost of ownership estimates are based on the following assumptions: initial flashlight purchase cost (LED Rechargeable, \$1.92; LED Dry Cell, \$1.28; Incandescent Dry Cell, \$0.64) (Johnstone et al. 2009), number of flashlight replacements per year (LED rechargeable=6, LED dry cell=6, Incandescent dry cell=2) (Tracy et al. 2009), daily use time (1 h), run time on a single charge or set of batteries (rechargeable batteries, 3.5 h; dry cell batteries in LED flashlights, 19 h; dry cell batteries in incandescent flashlights, 7.2 h) (Mink et al. 2010), rechargeable battery charging fee (\$0.26), and cost to replace dry cell batteries (\$0.38 per battery; each dry cell powered flashlight used two D-cell batteries; the tests were made with Eveready D-cells with a black colored casing) (Tracy et al. 2010a). Results reported in Table 1 are reported to the nearest USD

[a] Some people recharge on a fee basis while others have access to charging services without paying a fee. People indicating that they are able to charge without paying a fee commonly either have electricity in their homes or place of work, while those without access typically report paying approximately \$0.26 per charge (Tracy et al. 2010a)

LED flashlight sales likely to grow due to favorable economics

Although LED flashlights have been shown to perform poorly, have short lifespans, and lead to serious levels of consumer dissatisfaction, they nonetheless have achieved rapid sales growth (e.g., see Johnstone et al. 2009). This may be explained in part by the fact that the incumbent alternative, the incandescent dry cell battery-powered flashlight, is initially dimmer and—even after accounting for the short lifetime of the LED products—is generally more costly to operate. Based on reported flashlight use patterns in Kenya, frequent end users of flashlights, i.e., those using a flashlight for 1 h per day, can save an estimated 50 % of the cost of owning and operating a LED dry cell flashlight relative to the cost of a similar use pattern with an incandescent dry cell flashlight. An even greater cost savings, 70 %, can be achieved by owning a LED rechargeable flashlight; however, these high levels of savings require that users are able to recharge their flashlights without paying a fee, which is not always the case (Table 1).

In other words, very low-quality LED flashlights are being purchased in large numbers in Kenya and elsewhere in Sub-Saharan Africa because they are very inexpensive to purchase and because they typically provide economic benefits relative to commonly available types of incandescent flashlights. As a result, there is a robust and growing market for very low-performance LED products.[5]

LED flashlights and market spoiling

While the shift from incandescent to LED flashlights provides some economic benefits to users, the introduction of low-quality LEDs involves a number of drawbacks as well. First, the widespread use of very low-quality LED flashlights minimizes the benefits that could accrue to flashlight users. Improvements that would involve fairly modest increases in price could result in substantially better performance, and lower lifecycle cost. However, if buyers are unable to reliably identify the improved flashlights from their lower quality counterparts, manufacturers may be hesitant to offer them.

Second, the widespread use of low-quality LEDs can lead to a market-spoiling effect for higher-quality LED lighting systems, including high-quality off-grid LED lights (frequently solar-charged) used in other applications such as room and task lighting. The market spoiling hypothetically occurs when end users of LED flashlights associate LED technology with inferior quality, compromising the market for higher-quality LED products.

Evidence from our study of market sales of LED lighting products in Kenya indicates that a market spoiling effect that is linked to end user experience with low-quality LED flashlights may already be delaying and depressing sales of higher-quality LED lighting products. LED task-lighting systems were offered to small off-grid businesses (e.g., vegetable sellers and kiosk vendors) that used kerosene lighting during evening time business hours; the lighting needs of these vendors are similar but not identical to the wider household lighting market (Radecsky et al. 2008; Alstone et al. 2014). In the study, representatives of small off-grid businesses in two Kenyan towns (Karagita and Maai Mahiu) were interviewed to collect information about their lighting use patterns, expenditures, and experiences. In addition, detailed kerosene lighting use data were collected from a subset of 23 of the businesses. A rechargeable LED task-lighting system was then offered for sale to each of these businesses. The LED lighting systems, which were custom assembled by the research team from commercially available components, were sold at a price of 700 Kenyan Shillings (approximately US$ 9.30), and offered with a 1-year full money back guarantee.[6]

A total of 14 businesses chose to purchase a lamp, while 9 declined the offer. Analysis of survey data reveals that, at the time of the purchase, 11 of the 23 businesses had prior experience with LED technology while 12 had no prior experience. In all cases, the prior experience included knowledge of the low-cost, low-

[5] Note that one consequence of the high sales volumes and short useful lifetimes is the generation of significant solid waste when failed LED flashlights are discarded. Additionally, rechargeable LED flashlights, which make up a substantial fraction of those sold, utilize sealed lead acid (SLA) batteries. Disposal of flashlights with SLA batteries produces considerable hazardous waste. In Kenya, the quantity of lead that enters the waste stream annually as the result of LED flashlight disposal is estimated to exceed 1,000 metric tons (Tracy 2010). Exposure to lead has been shown to cause a variety of adverse health effects including physical and mental development impediments in children, cerebral and kidney diseases, and cancer.

[6] The LED lamps offered for sale in the study at the 700 KSh per unit price could be charged using grid electricity. The units could also be charged using solar power; the purchase price with the solar charging option was 1,500 KSh. All of those who chose to purchase bought the lower priced unit that allowed for grid-based charging only (Radecsky et al. 2008).

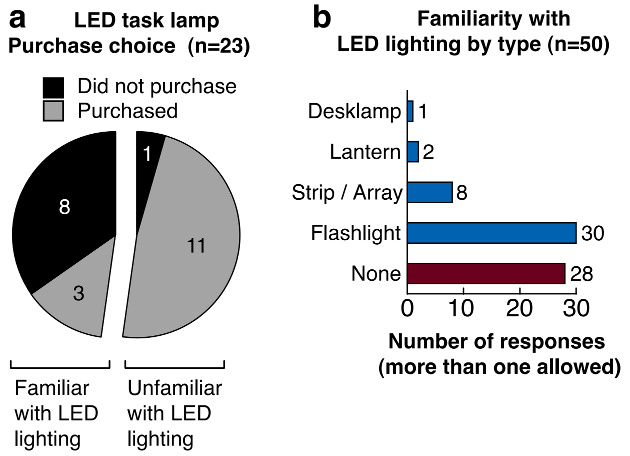


Fig. 8 **a** LED lighting system purchase choice for two groups among the 23 who were given the option to purchase: those who were and were not familiar with LED lighting in general. Familiarity was a statistically significant (p=0.0028) factor for predicting purchase choice. **b** Baseline familiarity with LED lighting among 50 night market vendors, including an option for "none". Alstone et al. (2014)

quality LED flashlights discussed above. It is notable that 8 of the 11 businesses that reported prior experience chose not to purchase a LED lighting system, while 11 of the 12 who were unfamiliar with LEDs agreed to buy (Fig. 8). This suggests a strong market spoiling effect in which those with prior experience with poor quality LED products were skeptical of the technology even in a situation where a warranty was offered. This finding has significant negative implications for producers of good-quality LED lighting systems, as it indicates that potential buyers must overcome existing skepticism of the technology caused by prior experience with widely available low-quality LED flashlights.

While flashlights have different form factors and typical patterns of use than off-grid lights used for more general applications such as task and room lighting, numerous field observations indicate that many potential users link their experiences with LED flashlights with other types of LED-based lighting systems. As one example, a shopkeeper who sells good-quality LED lights told our team (paraphrasing), "I expect LED flashlights to last about two weeks…this other light is much better quality so I expect it to last four weeks." The reality is that the better-quality light he was referring to should last 1–2 years or more, but his experience with LED flashlights set a very low baseline

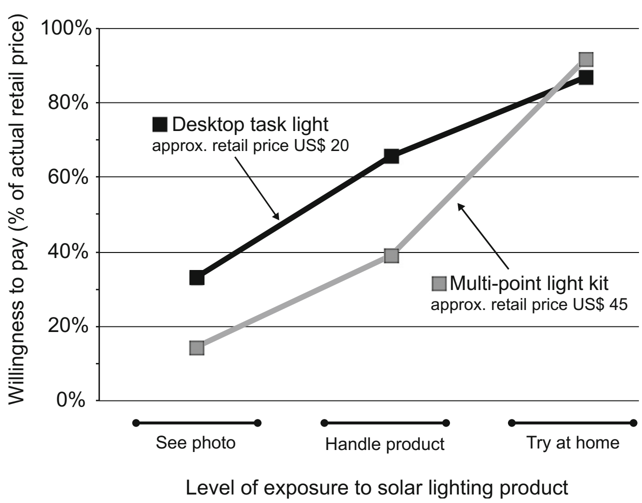


Fig. 9 Evolving willingness to pay for two good-quality solar lighting products, a desktop lamp with an approximate retail price of US$ 20 and a multi-point light kit with an approximate retail price of US$ 45, shows that the WTP value approaches the retail price as exposure increases. The values shown are the average of results from five countries (Ethiopia, Ghana, Kenya, Tanzania, and Zambia) in a market research survey (Lighting Africa 2010a, b) that was conducted in 2008. The sample size of participants was 5,000 for seeing photos and 100 for handling products and trying them at home; the sampling was evenly distributed geographically. This figure is adapted from data and analysis in Lighting Africa (2010a, b)

for quality. He was willing to assert that good-quality lights were twice as good as LED flashlights but not qualitatively different and 25–50 times better. Making these links is sensible considering the visual similarity between the LEDs used in flashlights and those used in many other LED lighting products. Moreover, LED flashlights and other types of LED-based off-grid lighting products frequently use the term "LED" on their packaging, which strengthens the idea that similar technology is in use.

Evidence from two willingness-to-pay (WTP) studies on off-grid lighting supports the argument that there is significant information asymmetry in the market that arises from a lack of exposure to and information about good-quality lighting products (Lighting Africa 2010a, b; Brüderle 2011). In both studies, potential end users exhibited an "evolving" WTP for good-quality lighting products, meaning that the acceptable price for a lighting product increased significantly with increasing exposure and experience—as people had better information from exposure and experience with products their confidence in the technology increased. In the study (with results illustrated in Fig. 9), survey respondents across five countries in Sub-Saharan Africa (Ethiopia, Ghana, Kenya, Tanzania, and Zambia) were asked about WTP after three levels of product exposure: having only seen a photo and description of products, being allowed to handle products before an in-home trial, and after the in-home trial. For two different solar lighting products (a desktop task light and a multi-point lighting kit), the average initial WTP after only seeing a photo was close to the price of commonly available LED torches, about US$ 5, and only a fraction of the actual retail price for these better performing, better-quality products. Users who were given the opportunity to handle the products had a higher WTP (70 % higher for desktop task lights and 160 % higher for multi-point light kits). After in-home trials in which users gained practical experience with the products, their WTP approached the retail prices.

A similar trend was observed by Brüderle (2011) in a field trial in Uganda, where users with in-home experience tended to have higher WTP than those who only saw or handled the products. The evolving WTP results underpin how a lack of practical exposure to good-quality lighting products results in depressed WTP (and implicitly also in depressed confidence in the technology).

Policy recommendations

Policy measures aimed at addressing the information market failures we have observed could lead to improved product quality, higher consumer confidence, an increase in transactions that mutually benefit buyers and sellers, and a corresponding net social benefit. Applicable measures include warranties and further investment in branding by the private firms producing high-quality products, voluntary certification and labeling programs designed to deliver information to potential buyers so that they can make informed choices, mandatory performance standards, and government regulations that ban poor performers from the market, if implemented successfully. Several efforts to address the issue are currently underway.[7]

Focus group work lead by author Tracy with support from several other authors of this article indicates that many potential buyers of off-grid lighting products in Sub-Saharan Africa have a strong preference for a recognizable quality label that differentiates good-quality products from the others in the market. In the absence of a recognizable label—the status quo—focus group participants indicated that they are left guessing about the quality of products and veracity of performance claims from manufacturers.

Another important result from the focus groups is a list of the five most important pieces of information consumers wish to know before purchasing a lamp. In the context of information market failure, these results can be interpreted as the highest priority missing pieces that address the information gap around off-grid lighting products. Manufacturers, governments, and market support programs that seek to fill those gaps using communication vehicles such as product advertising, quality labels, consumer awareness campaigns, or other interventions should consider steps aimed at delivering the missing information. The five key pieces of information, in rank order, are: brightness, warranty terms, robustness, the presence of mobile phone charging features, and daily run time per battery charge. It is notable that potential buyers have split priorities between performance related (brightness, run time, and mobile phone charging) and durability related (warranty and robustness) features. A successful intervention will account for

[7] For example, see http://www.lightingafrica.org, http://light.lbl.gov, and http://www.cleanenergyministerial.org/SLED/index.html.

both, ensuring that buyers are protected from substandard durability and are informed about the real performance levels of products in the market.

To address the asymmetric information problem, Lighting Global has created a product-testing program. As an indicator of the efficacy of this policy strategy, as of March 2014, 81 off-grid lighting product manufacturers had submitted 110 products for testing. Of these, only 45 (41 %) initially met the minimum quality standards. Of the 65 products that initially failed, nearly half (31) were improved by the manufacturers and successfully met the standards upon retesting.[8] In effect, the testing process thus far has directly led to almost a doubling of the number of quality products on the market.

Conclusions

LED flashlights have rapidly become widely available, and are being adopted as a replacement for incandescent flashlights. Tests in the laboratory and end user feedback have shown that the typical lifetime for the LED flashlights that are currently available is on the order of months, contrary to the claims made on their packaging. Their primary failure mechanisms are rapid lumen depreciation, battery failure (in the case of rechargeable products), and mechanical failure from fatigue or being dropped. However, consumers continue to purchase them, which is likely due to a combination of their higher initial light output and lower operating costs compared to dry cell incandescent alternatives.

The widespread availability and consistently low-quality of inexpensive LED flashlights has had a spoiling effect in the emerging market for higher-quality off-grid lighting systems based on LED technology. While the reversibility of this effect is not yet known, we can confidently say that market development has been depressed and delayed.

If LED lighting is to achieve its potential as a superior substitute for fuel-based lighting, effective measures that address this information market failure problem are needed. Key measures include independent product testing, certification, labeling, warranties, and associated end user education and exposure to high-quality products. Mandatory measures could be applied if voluntary measures do not suffice. Such market interventions would remove asymmetries in the consumer information environment and increase the uptake of new off-grid lighting technologies that stand to improve consumer economic welfare while securing health and environmental benefits.

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[8] See http://www.lightingglobal.org/activities/qa/statistics/.

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