FLASHLIGHTS IN KENYA: REVEALING THE SOCIAL, ECONOMIC, HEALTH AND ENVIRONMENTAL IMPLICATIONS IN THE ABSENCE OF QUALITY ASSURANCE

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ABSTRACT

FLASHLIGHTS IN KENYA: REVEALING THE SOCIAL, ECONOMIC, HEALTH AND ENVIRONMENTAL IMPLICATIONS IN THE ABSENCE OF QUALITY ASSURANCE

Jennifer Lee Tracy

For the 1.6 billion people in the world who lack access to electricity, the flashlight serves as a simple but important lighting device. In contrast to traditional incandescent flashlights, incorporating light emitting diode (LED) technology into flashlights presents a potentially less polluting, more efficient and cost-effective alternative lighting source. To avoid market spoiling as LED technology is introduced into off-grid lighting markets it is essential that quality be assured. This study addresses the quality of flashlights available to low-income flashlight users in Kenya. Lab-based performance testing of three commonly used models shows that flashlights perform substantially below rated specifications. Models tested had battery capacities that were 50% below rated levels and required up to 25% more time to charge the battery than advertised. Frequent users of flashlights expressed high levels of dissatisfaction with available flashlights; 87% reported having problems with their flashlight in the last six months. Failed LEDs (23%), water leakage (21%), and batteries no longer keeping their charge (16%) were among the most common problems. The median reported lifespan of a flashlight was two months. Users interviewed indicated that the cost of flashlight ownership absorbed up to 7.4% of their annual income. In addition, the potential health and environmental risks associated

with flashlight use are substantial. Estimates indicate that more than 700,000 kg of lead are discarded and over 30,000 m^3 of waste are produced annually from the use of low quality flashlights in Kenya. Scenarios illustrating the impact of marketing an affordable, improved quality flashlight indicate a potential 80% reduction of waste and lead disposal and up to a 65% cost-savings for flashlight users. Results obtained from this study are useful for creating a framework for quality assurance of low-cost flashlights products, helping to reduce the social, economic, health and environmental implications of low-cost flashlights in Kenya and elsewhere around the world.

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INTRODUCTION

For over 100 years, the flashlight has been one of the most important portable electric lighting devices. It provides a sense of security for billions of people, many of whom have low incomes and no direct access to conventional grid electricity. Over the last century the flashlight has gone through multiple transformations. Most recently, flashlights that use LED technology have quickly permeated the portable lighting market around the world. LED flashlights are an important early manifestation of LED lighting in the developing world that can serve as a platform for – or deterrent to – the diffusion of LED technology into the broader off-grid lighting market. Many LED flashlights use rechargeable lead acid batteries. The lead in the batteries represents an important source of hazardous waste, and flashlight durability is thus an important determinant of the rate of waste disposal. Unfortunately, in developing countries such as Kenya, many flashlights, including especially the inexpensive units widely used by low income people, are poor in quality. As my research shows, this not only leads to social and economic consequences including consumer dissatisfaction and price inequities for electric lighting, but also to troubling health risks and environmental impact concerns.

Initial field observations from Kenya clearly indicate the importance of the flashlight in people's daily lives, while also making apparent the high level of user dissatisfaction with the poor performance of the flashlight products currently available for purchase.

In this report, I will begin by providing a contextual background that explores the need for this study. This is followed by an explanation of methods, describing my approach to data collection, including a description of my study sites and the individuals participating in my fieldwork. Next, I present my results and discuss my findings, highlighting the need for change and possible strategies of action that can addresses the issues uncovered by my research. In the conclusion, I emphasize how the results from this research can be used to support efforts to ensure quality in the flashlight market in Kenya and other low-income off-grid markets around the world.

My aim is to validate the important role of the flashlight in people's lives in Kenya and to systematically assess the quality of products currently available. I have conducted laboratory performance testing on flashlights procured in Kenya, providing quantifiable data on the performance of these products. In addition, I have closely examined three distinct groups of flashlight users: Night Watchmen, Bicycle Taxi Drivers, and Households. These groups were selected because they are frequent and, in some cases, intensive users of flashlights. The goal at hand is to highlight the experiences, perceptions, and preferences of flashlight end-users to better understand the quality of flashlight products available in the Kenyan off-grid lighting market.

Based upon the end-user data collected, I have estimated the one-year cost of ownership for a range of flashlights currently available in the Kenyan lighting market. Through this analysis I show the economic benefits of higher quality flashlights.

To further emphasize the value of higher quality flashlights, I have examined the health and environmental implications of flashlight use. This assessment looks closely at the solid waste and environmental and health aspects of flashlight disposal.

In my literature review I was not able to find any prior studies that detailed the social uses of flashlights in developing countries. With the exception of recent work by my colleagues and me (e.g. Tracy et al. 2009, Johnstone et al. 2009), there were also no studies that focused on the quality of flashlights available to low-income consumers. This is, nonetheless, an important topic; solutions could potentially benefit billions of people by reducing the cost to low-income flashlight users and by limiting the environmental ramifications of poor quality flashlight products. My research offers a crucial starting point to help ensure higher quality products become available to flashlight users in the developing world. My study evaluates the performance of flashlights, documents the importance of the flashlight and use patterns, and identifies the implications of flashlight products currently available. I addition, I also indentify product features favorable to the consumers. These insights are all elaborated using Kenya as a case study.

BACKGROUND

Several concepts exemplify the need for this study. Through outlining a brief social history of flashlights and their global importance I will illustrate the numerous flashlight evolutions that have taken place in the last century and how flashlights came to be relied upon, often as a sole source of electricity, by rural populations. Next, by addressing the issue of energy access I explain why rural people rely so heavily on flashlights. I follow that with a discussion of flashlight quality assurance concerns. I then describe the general health risks and environmental impacts associated with flashlight components, focusing on chemical toxicity and waste accumulation at the point of disposal. In the last section of the background I provide a brief description of Kenyan demographics and illustrate the presence of flashlights within Kenya.

Social History of Flashlights

The turn of the 20th Century saw the development of a technology that has impacted the lives of people worldwide. Introduced by the Eveready Company in 1898, the flashlight has become one of the most fundamental portable electric lighting devices (Eveready 2010). Unlike technologies that are rapidly introduced into a country, which often exhibit early market failure, flashlight technology has been successfully adopted by people around the world (Graham 2004). For approximately 50 years the flashlight went through a market development path. Flashlights first entered into urban markets, become a mature technology,[1] and eventually made their way into rural markets (Graham 2004). It was this process that has enabled people in New York City as well as those in the Rift Valley of Kenya to utilize and rely on this transformative technology.

One hundred years after the introduction of the flashlight, a new transformation took place that fundamentally changed the flashlight industry. In 2001, the first flashlight utilizing light emitting diode (LED) technology was manufactured (Rich 2008). Prior to the introduction of LED flashlights, incandescent bulbs were the dominant technology. Typically powered by disposable dry cell batteries, a small incandescent flashlight consumes energy at a much higher rate than a flashlight utilizing LEDs; a battery will last 10 to 15 times as long powering a LED versus an incandescent. A field study led by Light Up the World Foundation in 2005 showed that Nepali, Indian and Sri Lankan villages favored LED technology to that of incandescent bulbs, noting that the real advantage was that the batteries in the LED flashlight, "provide a useful level of light for well in excess of 500 hours, compared to an absolute maximum of 50 hours for the incandescent version" (Peon et al. 2005). LED lighting technology itself has the potential to last up to 50 times longer than an incandescent bulb. LEDs are also more efficient, have greater durability, do not cause heat build up and have a low maintenance cost (Mills 2002, Energy Efficient Lighting 2004). Due to the directionality of LED illumination, however, LEDs have been less favorable for ambient lighting.[2] Field studies have shown that people prefer LEDs for task lighting and flashlight applications

[1] A mature technology is characterized by being robust, having locally accessible replaceable parts, a simple design that permits local technician to service, dependability, and affordability (Graham 2004).
[2] Though this may be changing as manufacturers are beginning to diffuse the LED illumination.

where directionality is expected (Du et al. 2005, Jones et al. 2005, Apte et al. 2007). All these benefits of LED technology, however, may be compromised if the LEDs are produced poorly. Cheaply made LEDs, often found in low cost LED products, are known to have inferior quality as compared to LEDs that are more expensive to produce (RightLight 2009).

One more recent modification to flashlights, especially in the developing world, is the increasing use of rechargeable sealed lead-acid (SLA) batteries in place of the disposable dry cell batteries (Radecsky et al. 2008). This transition is valuable in locations where electricity is accessible. An economic analysis of lighting products in Kenya showed that people who use rechargeable lighting products may spend less money annually on lighting than those using products that require dry cell batteries (Radecsky 2009). However, the many people in developing countries that live a significant distance from grid electricity may not be able to benefit from the advantages of rechargeable SLA batteries. Rechargeable SLA batteries are not problem-free, though, and have their disadvantages relative to the dry cell batteries commonly found in Kenya. SLA batteries are more toxic and come with an increased potential of health and environmental impacts compared to the zinc-carbon disposable dry cell batteries commonly used in Kenya, as will be described in more detail below.

Energy Access

In the world today, 1.6 billion people lack access to electricity, and, according to the International Energy Agency, unless new approaches and policies are adopted, 1.4

billion people will still lack access to electricity in 2030 (World Energy Outlook 2002). In Sub-Saharan Africa alone, nearly 75 percent of the population, roughly 550 million people, do not have access to electricity (Electricity Access 2009). In this context, access is defined as the number of people with electricity in their homes either on-grid or off-grid (World Energy Outlook 2002). It does not, however, indicate the number of people who have electricity in their homes that is intermittent and unreliable, a commonality among newly developing grid-electricity systems in developing countries. Nor does it account for the people who have electricity in their homes, but cannot afford to use it. A more inclusive definition of access, such as that put forth by Ribot and Peluso, defines access as not just the *right* to benefit from things, but as the *ability* to benefit from things (2003). Using this definition would suggest the number of people without access to reliable electricity is likely to be much higher.

Sources of light for people without access to electricity often come from candles, kerosene lamps, open fires, dung and diesel lamps (Davis 1997, Reiche et al. 2000, Jones et al. 2005, Peon et al. 2005, Mills and Jacobson 2008, Schultz et al. 2008). These sources have harmful impacts upon both human health and the environment (Smith and Schare 1995, Mills 2002, Muller et al. 2003, Apple et al. 2010). The use of light emitting diode (LED) based lighting products, however, has numerous potential advantages. They do not emit harmful particulate matter, as does the burning of candles, biomass and carbon-based fuel sources. Nor do they require the harvesting of scarce natural resources, as in the case of biomass for fires. While flashlights do not normally provide a substitute for kerosene and other highly inefficient lighting fuels, they are an important early use of LED lighting in the developing world and serve as a platform for the diffusion of the technology into the broader lighting market.

Furthermore, the quality and quantity of light output of many of these fuel-based sources is disproportionately small compared to their operating cost. One in four people worldwide obtain their lighting from fuel sources, candles or flashlights. These sources equate to 17% of the global lighting energy costs, but they only result in 0.1% of the lighting energy services (Mills 2005, Mills and Jacobson 2008). Because of limited energy options available to many of the world's poor, low income people tend to pay much more per unit of energy than do more affluent people (Cecelski 2000). Many low income families in the developing world pay roughly the same amount as a typical North American family, but receive less than 0.2% of the light (Peon et al. 2005, Schultz et al. 2008). In the case of kerosene lighting, users pay 150-times more per unit of useful lighting service than people who use AC powered compact fluorescent lamps (Mills and Jacobson 2008). While fuel-based lighting has long been expensive, its cost has increased still further in recent years. From 2004 to 2008 kerosene prices in Kenya quadrupled from 20 Ksh/liter to 85 Ksh/liter (Ksh = Kenya Shilling) before dropping to 60-65 Ksh/liter throughout 2009. For the more than 2 billion people that earn less than $2 per day, the increasing cost of lighting has a major impact upon their livelihoods (Radecsky 2009).

Solid-state lighting technology, including LED flashlights, has the potential to provide improved lighting and substantial health and economic benefits to the world's poor (Mills 2005, Apte et al. 2007, Schultz et al. 2008, Pokhrel et al. 2009, Apple et al.

2010). For those who are without access to electricity, a flashlight provides illumination that can be key to enhancing one's well being (Pachauri and Spreng 2003, Chaurey et al. 2004, Ezzati et al. 2004, Heffner and Fernstrom 2007, Kanagawa and Nakata 2007). Quality illumination has been shown to advance literacy, safety, and the ability to do productive work (Cecelski 2000, Gustavsson and Ellegard 2003, Shanko and Rouse 2005). The integration of LED-based lighting products into rural locations with limited access to electricity can play a key role in improving access to modern lighting, and in the process it can help address economic, social and health inequities. However, coming back to Ribot and Peluso's definition of access as the *ability* to benefit, there is reason for concern if the LED-based lighting products infiltrating the market are of poor quality. It is costly to frequently replace low-quality LED products that do not last beyond a few months; this cost may not be affordable to the potential low-income beneficiaries of LED lighting products. In this regard, if poor quality LED-based lighting products, including LED flashlights, enter into rural lighting markets, the people who could most benefit from their application may still lack access to a reliable form of the technology. Addressing energy access requires addressing quality.

Quality Assurance and Market Spoilage

Though the flashlight is a well-established technology, the quality of emerging LED flashlight products available in developing countries is of concern. LED flashlights have the potential to be far superior to incandescent flashlights. Preliminary performance testing of LED flashlights infiltrating the market in developing countries, however, shows poor product performance and thus threatens to cause market spoilage (Radecsky et al. 2008). Market spoilage occurs when end-users are led to believe a product will offer a certain level of performance (often times through the manufacturers advertising), but the product's actual performance is below indicated levels, creating buyer's remorse.

Within the last ten years, research about the quality of solar photovoltaic modules in Kenya has contributed to improved quality in the Kenya solar market (Jacobson et al. 2000, Duke et al. 2002, Jacobson and Kammen 2007). This research took place at a time when a few manufacturers had distributed poor quality amorphous silicon solar modules in the Kenyan solar market, leading many consumers to generalize inferior quality to all solar modules, even the high quality models. Quality assurance issues concerning solar and lighting products in general have also recently been addressed elsewhere around the world (Efficient Lighting Initiative 2004, Niewenhout et al. 2004, Sturm and Tienan 2005). These efforts emphasize the importance of both assessing product quality and publicizing the findings. Such assessments can help to deter market spoiling. When product quality information was made publicly available beginning in 1999 for PV products in Kenya, pressure was put on the manufacturers of low performing models of PV modules to improve or exit the market. This resulted in a stronger solar market and a better-served public, along with the conclusion that, "as solar markets develop throughout Africa, vigilant, effective, and transparent monitoring programs are needed to ensure quality and to protect the public interest" (Jacobson and Kammen 2005).

In recent years, several initiatives have started to address the quality of lighting products sold for off-grid use in developing countries. In 2005 the Lumina Project took hold, part of which includes an off-grid lighting technology assessment. Its research, conducted through the Lawrence Berkeley National Laboratory (a Department of Energy laboratory located in Berkeley, California) and the Schatz Energy Research Center (Humboldt State University), provides, "manufacturers, resellers, program managers, and policymakers with information to help ensure the delivery of products that maximize consumer acceptance and the market success of off-grid lighting solutions for the developing world" (Radecsky et al. 2008). In 2007, the Lighting Africa program, an initiative by The World Bank and the International Finance Corporation, was established to help cultivate the development of the lighting market in Africa, including a quality assurance program addressing the concerns of off-grid lighting products.

> "To shield African consumers from poorly performing lighting products and to avoid market spoilage, a product quality assurance program is underway to enhance consumer awareness, support industry in improving technologies appropriately tailored to the African consumer base, and boost confidence in new lighting products" (Lighting Africa 2008).

Presently, the range of LED-based lighting products in rural off-grid lighting markets is rapidly increasing; such is the case in Kenya. LED technology, and its application in flashlights in developing countries has the potential to provide a huge cost benefit to the 2.6 billion people in the world who live on less than $2 per day (World Bank 2008). Unfortunately, if LED flashlight products available to end-users in developing countries are of inferior quality, this benefit could be lost. To avoid this outcome, a better understanding of the social, economic, health and environmental implications of the current flashlight market is warranted. Furthermore, successful integration of LED-based lighting into consumer markets would be aided by assessing the quality of LED-based off-grid lighting systems currently available.

Empowering people to make informed purchasing decisions when buying lighting products requires product performance information to be accessible to the consumer. It is critical to set a quality standard in which products meeting that standard are publicly recognized, enabling buyers to understand the level of product quality prior to purchase. Communicating quality concerns to the manufacturers of LED-based lighting products is a vital component for developing a framework for quality assurance. Offering performance testing feedback to the manufacturers of LED-based lighting products, and providing a quality seal if quality standards are met, will help accelerate the availability of quality lighting products in the African off-grid lighting market. Such action has the potential to prevent market spoilage and to help establish customer confidence in LED-based lighting products, supporting a transition away from fuel-based lighting sources. The results of this study will help uncover the problems associated with low-quality flashlights in Kenya and help prompt action toward quality assurance. Beyond the concerns already addressed, low-quality flashlights also pose substantial health and environmental threats.

Health and Environmental Implications

The health and environmental impacts of flashlights can be analyzed at multiple levels. My analysis of these impacts focuses on a single phase in the life of a flashlight and examines the health and environmental impacts associated with the disposal of flashlights. To do this, I have broken the flashlight into the following components for analysis: LEDs, flashlight housing, and batteries (both rechargeable and non-rechargeable). I will examine the health and environmental impacts of each of these components. However, I will not focus on the impact of a flashlight's embodied energy, although that would be beneficial to explore in future research.[3]

LEDs, flashlight housing, and batteries contribute to the health and environmental implications of flashlights at the stage of disposal. The disposal of light emitting diodes (LEDs) have for the most part been assumed to be relatively benign. However, as LEDs become a mainstream technology, new research may prove otherwise. Gallium nitride, a semiconductor used to make LEDs, is the primary compound of concern when it comes to their disposal. However, little toxicology research has been done on LEDs so no definitive conclusion can be drawn at this time regarding their potential level of health risk (Shenai-Khatkhate et al. 2004). According to Material Safety Data Sheets (MSDS), gallium nitride is a skin, eye and respiratory irritant; however, its toxicity is not fully investigated (Safety 2003). The primary concern with the flashlight housing, which is principally made from either a polypropylene plastic or metal, is the fact that the materials do not break down and thus present a waste accumulation issue. The batteries

[3] Calculating the embodied energy entails examining the flashlight over its entire lifespan (from production to packaging to distribution and finally to disposal). Calculations include all the energy inputs, including the energy required to make the components (LEDs, plastic casing, wires, batteries etc.), energy required in making the packaging, energy in the transportation from manufacturer to end retailer, and energy required for disposal. This would be a valuable assessment to make, generating a more complete picture of the environmental and health impacts of a flashlight. Unfortunately, at the moment accounting for the embodied energy is not feasible, as the research necessary to make these calculations is beyond the scope of this study.

also pose a waste accumulation problem; disposable dry cell batteries more so than rechargeable batteries, as dry cell batteries are replaced numerous times throughout the lifespan of the flashlight.

The batteries are also the component that poses the greatest toxicity concern. This, however, is referring to the rechargeable sealed lead-acid (SLA) batteries, not the zinc-carbon non-rechargeable dry cell batteries. The most commonly found disposable dry cell batteries used in flashlights throughout Kenya are zinc-carbon based. Both zinc and carbon (and manganese which is used as the positive electrode material in zinc-carbon batteries) do not pose a significant threat to health or to the environment and the US Environmental Protection Agency (EPA) does not regulate zinc carbon batteries as hazardous waste (Batteries and the Environment 2001). Sealed lead-acid (SLA) batteries, the most common battery used in rechargeable flashlights, are a much greater threat due to their use of lead. Composed of 60% lead by weight (Linden 2002), SLA batteries are supposedly *sealed*; however, the lead inside can leak out posing both environmental and human health concerns.

Lead (Pb) is an elemental metal persistent in water and soil. The toxicity of lead has been known and observed for centuries (Walker and Wiener 1995, Lewis 1985). Modern science has been able to more closely evaluate the adverse health effects of lead exposure revealing that many ill effects can occur without any overt signs of toxicity due to chronic exposure to low doses of lead. As outlined by the Agency for Toxic Substances and Disease Registry, the most sensitive targets for lead toxicity are the developing nervous system, the hematological and cardiovascular systems, and the kidney (ATSDR 2007). Exposure to lead can cause a variety of adverse health effects including delayed physical and mental development in babies and children, interference with red blood cell chemistry, slight deficits in attention span, hearing and learning abilities in children, increased blood pressure in adults, abnormal neurobehavioral development in children, cerebrovascular and kidney disease, and cancer (EPA 1993).

There is a large body of evidence linking the myriad of aforementioned health effects to lead exposure; however, research has yet to conclude threshold doses of lead related to chronic low-dosage exposure (ATSDR 2007). Reference values for minimum lead levels in the body are not available because “it appears to be a nonthreshold toxicant” (EPA 1993). This means that exposure to lead; even at undetectably low levels, can still cause ill health. Such chronic low-dose exposure is likely the type of exposure most relevant to at risk populations in Kenya. As a result of observed disposal habits concerning flashlight batteries, it is presumable that over an individual’s lifetime a person will encounter inappropriately disposed of SLA batteries that potentially are leaching lead.

Preexisting physical conditions further complicate the assessment of health effects from lead. First of all, lead is a heavy metal that bioaccumulates in the body. Secondly, its effects vary widely based on age, health, and other factors. The Agency for Toxic Substances and Disease Registry reports that young children can absorb lead more efficiently than adults, 50% versus 15% (2007). Additionally, fasting can also have a significant effect on absorption of lead where under fasting conditions the retention of ingested lead is about 60% as compared with 4% when lead is ingested with a balanced meal (ATSDR 2007). In Kenya, where undernourishment affects 33% of the population (FAO 2005), the rate of lead absorption may be high, posing an even greater concern.

Regardless of the complexity of the issue, studies have made a strong correlation associating lead concentrations observed in blood or bone samples. Blood lead concentration levels ranging from <10 to >60 μg/dL have been directly linked to the progression of the adverse health effects previously mentioned (Table 1).

Table 1. Ranges of blood lead concentration levels corresponding to adverse health effects and distinguished among children, elderly adults and adults (ATSDR 2007).

Population	Health Effect	Blood lead (μg/dL)
Children	Neurodevelopment abnormalities	<10
	Sexual maturation	<10
	Depressed vitamin D	>15
	Depressed Nerve Conduction	>30
	Depressed hemoglobin	>40
	Colic	>60
Elderly Adults	Neurobehavioral effects	>4
Adults	Elevated blood pressure	<10
	Peripheral neuropathy	>40
	Neurobehavioral effects	>40
	Altered thyroid hormone	>40
	Reduced fertility	>40
	Depressed hemoglobin	>50

Currently, flashlights available in Kenyan use primarily SLA rechargeable batteries or carbon-zinc dry cell batteries. Other battery options available outside of Kenya may be beneficial if utilized within flashlights sold in Kenya. Nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and lithium-ion (Li-ion) are all battery types readily available in the world market. NiCad batteries, however, are no more favorable than SLA batteries since cadmium is a toxic substance that, if ingested by humans, can lead to serious health problems including respiratory and cardiovascular disease, liver and kidney problems (Buchmann 2003, ATSDR 2008), as well as pose a chemical burn risk (MSDSa). NiMH batteries are considered environmentally friendly, though the nickel is considered a semi-toxic substance that may cause allergic pulmonary asthma (MSDSb). Of greater concern are the electrolytes contained in NiMH batteries that in large amounts are hazardous and can cause respiratory and skin irritation and can produce chemical burns (Buchmann 2003, MSDSb). However, because NiMH batteries are considered to pose low health and environmental risk they can be discarded with other household waste, unlike NiCd and SLA batteries (Buchmann 2003). Lithium-ion batteries are also relatively benign and can be thrown out with regular household waste; however, most lithium batteries do contain toxic and flammable electrolytes that can cause chemical burns and irritate the skin and eyes (MSDSc). Regular lithium batteries (lithium-metal as opposed to lithium-ion) are also considered non-toxic, but because they contain metallic lithium, if they are not discharged fully they do present a toxicity concern at the time of disposal (Buchmann 2003).

It is clear that major health and environmental risks present themselves from the standpoint of flashlight disposal. Later, I will assess the magnitude of two such concerns, waste accumulation and lead disposal, and offer suggestions for change based on the information presented here.

Kenya as a Case Study

The importance of the topic considered in this research has been clearly established. The value a flashlight provides to people in developing countries is substantial; livelihoods depend upon the technology. Where product quality comes into question, it becomes necessary to address product performance and facilitate consumer awareness. A first step toward ensuring a stable and sustainable flashlight market is to examine currently available products from multiple angles, including technical performance testing, end-users experiences, economic consequences, and health and environmental impacts. Using this knowledge to develop policy could lead to a quality assured flashlight market. This research study addresses this first step with a focus on flashlight end-users in Kenya.

Located in Sub-Saharan Africa, Kenya shares borders with Ethiopia, Somalia, Tanzania, Uganda, Sudan and the Indian Ocean. It is a country of 39 million people, 78% of who live in rural areas and 50% of who live below the poverty line (CIA 2009). Forty percent of the population is unemployed. Of the workforce, 75% percent work in the agricultural sector while the remaining 25% work in the service and industry sectors

(CIA 2009). As of 2007/2008, the rural electrification rate was at 14% and 29.4 million people still lacked access to grid electricity (Human Development Report 2008).

Flashlights that use LEDs are emerging as the dominant technology for portable lighting in Kenya. According to a recent pilot study documenting the market presence of off-grid lighting technology in Kenya, rechargeable flashlights represent approximately 40% of the market while dry cell powered flashlights represent about 60% (Johnstone et al. 2009). Low cost LED flashlights with prices from $1 to $4 are now widely available in shops and markets throughout the country. The flashlight market in Kenya can be considered quite lucrative as over half of all Kenyan households report owning a flashlight (Kamfor 2002). While this shift from conventional incandescent technology to modern LEDs may appear to be a promising development, end users interviewed expressed a number of complaints about the quality and performance of these new flashlights. This raises concerns about the interests of low-income flashlight users, and it may also indicate the onset of a broader market spoiling effect for off-grid lighting products based on LED technology (Lighting Africa 2007, Mills and Jacobson 2008).

METHODS

In order to influence and improve the quality of flashlight products available in off-grid lighting markets found in developing countries, it is important to establish an understanding of the current flashlight market and the impacts it has on both users and the environment. To do this, I have examined flashlights and flashlight use from two angles. First, I have quantified through laboratory testing the performance of three common flashlights found in Kenya, and, second, I have conducted field evaluations in Kenya in which I asked flashlight users to report on their experiences with flashlights. The laboratory testing provided a series of seven qualitative performance parameters: battery capacity, time to attain a full battery charge, maximum initial illuminance, run-time, lighting service per charge, light distribution, and color rendering (see the following section for explanation of parameters). The field evaluations consisted of surveys documenting four main parameters of flashlight use: the prevalence of flashlights, use patterns, common complaints, and user preferences for an improved flashlight. Data reported by participants provided the basis for my cost analysis and evaluation of the health and environmental implications of flashlight use in Kenya.

Performance Testing

Product quality testing assessed the "out-of-box" condition, referring to the product's initial performance. Repeated testing of each performance indicator was not performed on each sample; this was to limit performance degradation due to wear and tear. The three models of flashlights, Flashlight A (Figure 1), Flashlight B (Figure 2), and Flashlight C (Figure 3) were purchased in rural Kenyan markets in January, 2009, just prior to testing. Five flashlights of each model were purchased for testing purposes. There were three main goals of this testing:

1. Compare the measured performance of flashlights to advertized levels for parameters where manufacturers provided rated specifications on the product packaging; the two parameters where this information was available were battery capacity and hours required to fully charge the batteries.
2. Estimate level of variability for key performance indicators within a product line (see box below), and
3. Compare key performance indicators among product lines.

Key performance indicators

- Battery capacity (mAh)
- Time to attain full charge (hr)
- Maximum initial illuminance (lux)[4] (at a distance of one meter)[5]
- Run-time (hr)[5]
- Lighting service per charge (lux-hr)[5]
- Light distribution: Area containing 90% of total lux (m^2)[6]
- Color rendering index (°Kelvin)

[4] Lux is a measure of illumination and is defined in terms of lumens per meter squared, where a lumen is a unit of measurement of the brightness coming from a light source.
[5] These tests were performed after the samples received a full charge from the Cadex 7400 battery analyzer. I use the "lux hours" metric rather than the more customary "lumen hours" because the energy services rendered by off-grid LED products (particularly flashlights) are often required to have a very narrow field of application. The lumen-hour metric would not capture the products' efficacy in applying the illumination to the desired task area.
[6] The value measured for comparison purposes is the area containing 90% of the total lux output measured within one square meter.

Figure 1 Flashlight A. Rechargeable 3 LED flashlight with a 1000 mAh rated battery.

Figure 2 Flashlight B. Rechargeable 4 LED flashlight with a 800 mAh rated battery.

Figure 3 Flashlight C. Rechargeable 5 LED flashlight with a 1300 mAh rated battery.

Data Collection

The three models of flashlights were tested at the Schatz Energy Research Center at Humboldt State University during an eight-week period in February and March of 2009. All samples were evaluated under the same test sequence: battery capacity, lamp discharge (measuring the third through fifth performance indicators), time to attain a full charge, light distribution, and lastly, color rendering. A description of how the seven performance indicators (see box above) were measured follows.

Battery Capacity: The capacity of the batteries was measured using a Cadex 7400 series battery analyzer and the associated computer software program, Battery Shop. The results were reported in milli-ampere hours (mAh). During this test the batteries were isolated electrically from the rest of the flashlight circuit. Measurements were made by discharging the battery at a constant current that corresponded to the 20 hour discharge rate as per the manufacturer's rated specification for battery capacity. The current and voltage pairs for each one minute time step were recorded by the Cadex' data logging system; each measurement had an accuracy of +/-1%. Prior to the battery discharge test, each of the batteries was fully charged using the Cadex 7400 battery analyzer at a 20-hour charge rate. After reaching a full charge each product also received a two to three hour trickle charge.

Time to Attain a Full Charge: A measurement of the time to fully charge the battery was carried out using the flashlight's internal charging system and 230 VAC, 50 Hz AC power (i.e., the type of power that corresponds to the Kenyan national grid). Because the laboratory where the tests were conducted is in the U.S., where the grid electricity is 120 VAC, 60 Hz, it was necessary to use an AC power supply to deliver the electricity for charging (Figure 4). The power supply consisted of a 230 VAC, 50 Hz true sine wave inverter that was connected to a 6 Volt battery. The battery was charged from an external source in order to maintain a constant state of charge throughout the test. The charging tests were conducted after the lamp discharge tests described below. As a result, all were discharged to a state of charge that corresponded to a light output corresponding to an illuminance of 5 lux at a distance of one meter. The associated battery voltages upon completion of the lamp discharge tests and prior to the grid charge tests were on the order of 2.6 Volts for the nominally 4 Volt sealed lead acid batteries used in the flashlights. During the grid charge test, the current input to the battery was measured using a CR Magnetics DC Current Transducer (model 5210-2; accuracy +/- 1.0%; output signal 0.5 VDC). Both the battery voltage and the voltage output from the current transducer were measured and recorded using a Hobo H08-006-04 data logger. The measurements were made at one minute intervals.

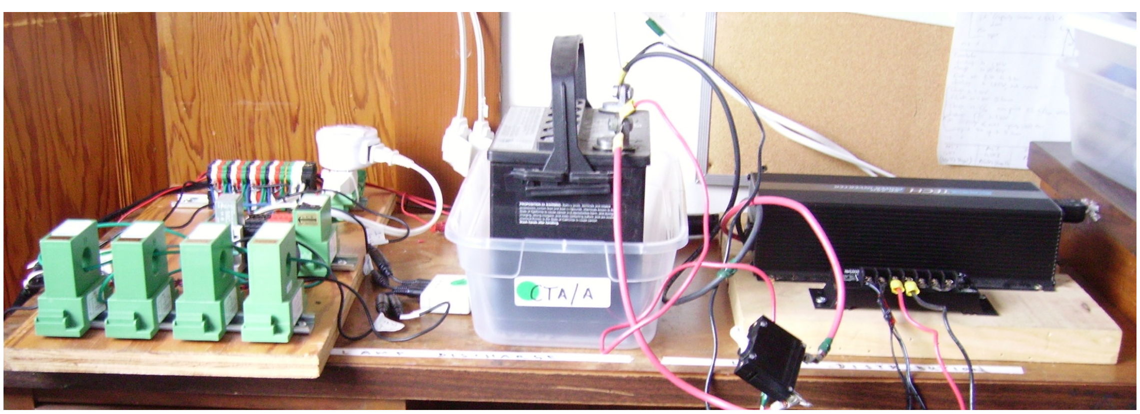

Figure 4 Kenyan Grid Simulator. 230V/50Hz pure sine wave inverter (far right), 6V battery to power the inverter (middle), datalogging equipment (far left).

Lamp Discharge Test: A lamp discharge test was used to measure the initial maximum illuminance at one meter, the number of light hours delivered from a fully charged battery (i.e., run time), and the number of lux-hours from a fully charged battery. For this test, the flashlight was mounted in a "dark box" at a distance of one meter from the illuminated surface. The dark box consists of a fully enclosed box approximately 122 cm (length) x 76 cm (width) x 76 cm (height) lined with black felt to eliminate reflection from the illuminance produced by the flashlight being tested. The box is designed with an illuminance meter mounted on one end in the center of the illuminated area and hardware mounted on the opposite end to hold the flashlight in place with a one-meter separation (Figure 5). During the test the current, voltage and illuminance at a distance of one meter were measured and logged at one-minute intervals. The flashlight was determined to be "fully discharged" when the illuminance at one meter dropped below 5.0 lux. This number is based on people's perceptions of when the light becomes too dim for use as measured in Kenya (Radecsky 2009).

Figure 5 Dark Box used to perform the lamp discharge tests. The datalogging equipment is on the outside of the box (right-hand side). The mounting device for the flashlight is located on the bottom end of the box and the illuminance meter is mounted on the opposite end.

Illuminance, current from the battery to the light, and battery voltage were all measured at one-minute intervals during the discharge. Illuminance was measured with an Extech Datalogging Light Meter (model 401036). Current was measured with a CR Magnetics DC Current Transducer (model 5210-2; accuracy +/-1.0%; output signal 0.5 VDC). The battery voltage and the output signal from the current transducer were measured with a Hobo H08-006-04 Datalogger (8 bit resolution; accuracy +/-3% of reading). Prior to initiating the test, the battery received a full charge on the Cadex 7400 battery analyzer at a 20-hour charge rate.

Distribution of Light Output: The distribution of light output from the flashlights was measured at 10 cm intervals along horizontal and vertical axes from a center point on a flat plane located one meter from the flashlight. Five measurements were made in each of the four directions from the center point, for a total of 21 measurements per flashlight (Figure 6). Data were recorded using the Extech Datalogging Light Meter (model 401036 [precision 0.01 Lux; accuracy +/-3% of reading]). Prior to testing, the flashlight battery was fully charged using the Cadex 7400 battery analyzer.

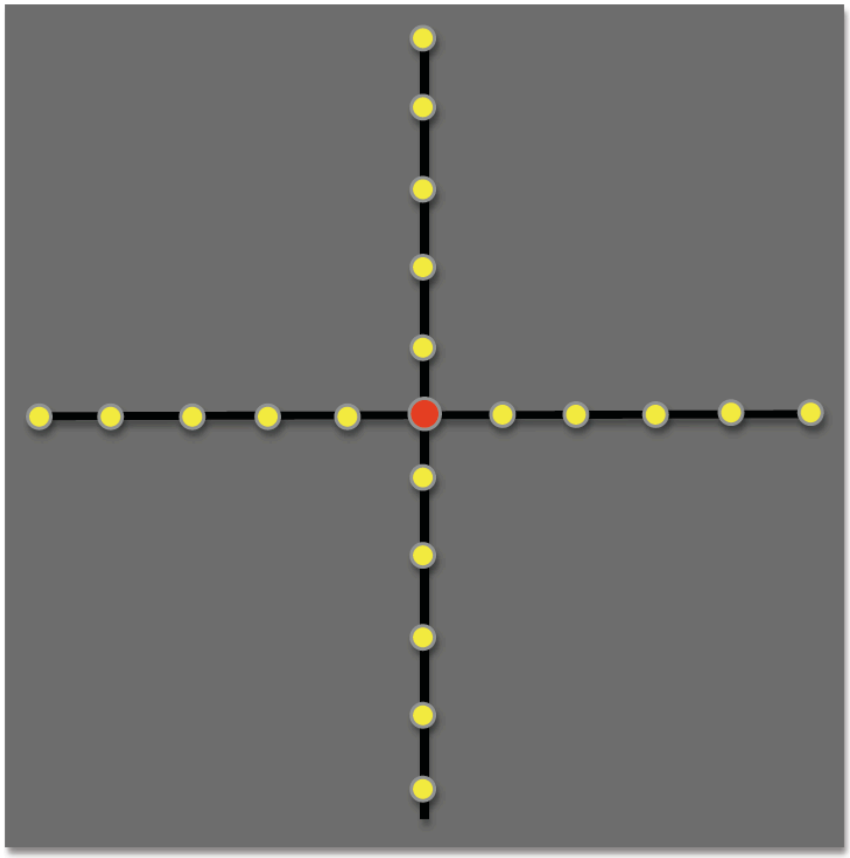

Figure 6 Diagram of the light distribution set-up. The red circle represents where the center of the flashlight beam is focused. Illuminance measurements are taken at all yellow and red circles, which have a distance from one another of 10 cm.

Color Rendering: The color rendering test involved measurement of the correlated color temperature (CCT) in degrees Kelvin. Higher color temperatures (5000 K or more) correspond to "cool" (green–blue) colors and lower color temperatures (2700–3000 K) correspond to "warm" (yellow–red) colors. Moderately cool-colored light is often considered better for visual tasks, while warm-colored light is preferred for indoor lighting. Color is ultimately a matter of end-user preference. Color rendering was measured in a "dark box" at the center of illumination at a distance of one meter from the illuminated surface. The flashlight's correlated color temperature (CCT) and CIE 1931 (x, y) chromaticity diagram values were recorded using a Gigahertz-Optik HCT-99 Color Meter (Sampling rate: 1ms, Color uncertainty: <<1% with CIE standard illuminant A[7]). When the CCT was above approximately 20,000 K, the color meter records only the x,y coordinates. In these instances an equation is used to determine the CCT based upon x and y CIE 1931 coordinates.[8] Prior to testing, the flashlight batteries were fully charged using the Cadex 7400 battery analyzer.

Data Analysis

Data were collected from five units each of three flashlight models, for a total of 15 flashlights, although complete sets of measurements were collected for 13 flashlights.[9] The performance of the flashlights allowed for comparisons between rated specifications and measured values, comparisons between models, estimates of the performance variability within each model, and identifies correlations between performance indicator. Minitab 15 statistical software was used to for data analysis. The variability among the five samples for each model was determined by calculating the coefficient of variation (CV) for each performance metric.

[7] *CIE standard illuminant A* is intended to represent typical, domestic, tungsten-filament lighting. Its relative spectral power distribution is that of a Planckian radiator at a temperature of approximately 2,856 K. CIE standard illuminant A should be used in all applications of colorimetry involving the use of incandescent lighting, unless there are specific reasons for using a different illuminant (International 1999).
[8] CCT x,y conversion equation, see Appendix A for definition of terms (Hernandez-Andres et al. 1999)
$$\mathbf{CCT = A_0 + A_1 \exp(-\mathit{n/t_1}) + A_2 \exp(-\mathit{n/t_2}) + A_3 \exp(-\mathit{n/t_3})}$$
[9] During testing, one of the Flashlight A samples malfunctioned, and data for color rendering and time required for a full charge were not obtained. Also, one of Flashlight C samples malfunctioned after the battery capacity test, thus all six additional performance indicators were not measured.

The variability in each performance metric among flashlights from the three product lines (i.e., models) was assessed using one-way Analysis of Variance (ANOVA). When assessing the mean difference across models, the equal variance assumption was met in all cases except for color rendering.[10] In the case that violated the equal variance assumption, the Kruskal Wallis Nonparametric Analysis of Variance test was utilized.[11] In addition, because the color rendering data were not normally distributed, CCT values were $\log_{10}$ transformed prior to performing the Kruskal Wallis test. In all cases where the ANOVA tests were used, Tukey's pair-wise comparison[12] was utilized to further indicate which flashlights differed from one another in each metric and Bonferonni confidence intervals[13] were generated to illustrate the directionality of the pair-wise comparison.

To compare the performance of flashlights to advertised levels, a one-sample t-test at a 5% significance level was used to compare the sample data to a) the rated specification for battery capacity (mAh), and b) the number of charging hours required to receive maximum light output. Significant correlations between performance indicators were determined using the Pearson Correlation at a 5% significance level.

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[10] The ANOVA test assumes that each of the groups being compared has the same within group variance. Levene's F-test was used to determine if this condition was met for each performance indicator. In cases where the condition was not met, a Kruskal Wallis test was used in place of the ANOVA test, as this alternate test does not require equal variances (Ramsey and Schafer 2002).

[11] The Kruskal Wallis Nonparametric Analysis of Variance test is a method for testing equality of population medians among groups. It is similar to a one-way ANOVA test; however, unlike the ANOVA test it does not require meeting the assumption of a normally distributed population. The Kruskal Wallis test does assume an identically-shaped and scaled distribution for each group, except for any difference in medians (Ramsey and Schafer 2002).

[12] Tukey's test is a single-step multiple comparison procedure and statistical test generally used in conjunction with ANOVA to find which mean values are significantly different from the others (Ramsey and Schafer 2002).

[13] The Bonferroni method is a simple method that allows many comparison statements to be made (or confidence intervals to be constructed) while still assuring an overall confidence coefficient is maintained. This method applies to an ANOVA situation when the analyst has picked out a particular set of pair-wise comparisons, or contrasts, or linear combinations in advance (Ramsey and Schafer 2002).

Field Evaluation

All field evaluation data collection was performed between May and July, 2009 except for follow up data collection with the night watchmen (further explanation detailed below).[14] Surveys were administered to three groups of people, all frequent users of flashlights, in two Kenyan towns. Maai Mahiu and Nakuru served as my study locations. Survey participants included night watchmen (Appendix B. Photo 1), bicycle taxi drivers (Appendix B. Photo 2 and Photo 3) and off-grid households (Appendix B. Photo 4 and Photo 5).

Surveys were designed to learn more about how these groups of people use flashlights, what problems they have encountered with flashlights and features they would desire in an improved flashlight (Appendix C). Responses from the surveys were also used for a one-year cost analysis of flashlight use and an assessment of the health and environmental impacts of flashlight use. Maina Mumbi, a Kenyan research colleague, and I administered the survey to a total of 46 people. The surveys were verbally administered in Swahili and/or Kikuyu by Maina and translated into English by Maina. The night watchmen surveys (n=15) took place in the small truck stop town of Maai Mahiu. The bicycle taxi driver surveys (n=15) took place in Nakuru. The household surveys (n=16) took place in Maai Mahiu with off-grid households. In addition to the surveys, seven of the night watchmen also received a new Yage 3166 flashlight with an integrated datalogger (Appendix B. Photo 6 and Photo 7) and were

[14] Fieldwork was approved by the Research and Graduate Studies Institutional Review Board at Humboldt State University (approval number: 09-22).

asked to use it as they normally would, allowing it to replace for their current flashlight. The datalogger within the flashlight recorded the time stamp, battery voltage, and battery current, providing use pattern data supplementing the use pattern data reported on the survey (Appendix B. Photo 8). The recorded data from the dataloggers were downloaded and emailed to me on a weekly basis from July until December 2009 by a research assistant in Maai Mahiu.

Maai Mahiu

Located in Kenya's Rift Valley, approximately 46 miles northwest of Nairobi (Figure 7), Maai Mahiu is a small truck stop town with a population of approximately 30,000.[15] Maai Mahiu residents are predominantly Kikuyu (one of Kenya's forty ethnic groups). Major sources of income for residents include agriculture, animal husbandry, *jua kali* labor (those who work with their hands, i.e. mechanics, seamstresses), quarry excavation, small business, and self-employment, including the night watchmen. An average family in Maai Mahiu makes around 5,000 Kenya shillings (Ksh) per month, roughly \$65. The town center is densely populated with small-businesses on either side of the main highway that passes through from Nairobi to Narok with residential housing spanning outwardly in all directions, encompassing an area of roughly ten square miles. Grid electricity was brought to the town in 1998; however, the majority of residents do not have electricity access in their homes due to the high installation costs. The electricity is primarily utilized by the businesses in the town center, though there is

[15] The population size is an estimate made by my colleague Maina Mumbi who resides in Maai Mahiu (Mumbi 2009).

considerable intermittency in the service and blackouts are frequent. The night watchmen and the household participants both lived in Maai Mahiu.

Nakuru

Located 86 miles north west of Nairobi (Figure 7), Nakuru served as the location for examining flashlight use by bicycle taxi drivers. With a population of over 230,000, Nakuru is the fourth largest urban center in Kenya (KNBS 2007).[16] Nakuru is considered a more cosmopolitan city with its residents coming from locations all throughout Kenya. Agriculture, manufacturing and tourism are the primary industries contributing to the economy, and in recent years Nakuru has developed a reputation as an academic center with multiple universities, colleges, and technical training institutes. The average monthly income is higher than that found in Maai Mahiu, however the income range is much greater (Mumbi 2009). Where a bicycle taxi driver makes roughly 9,800 Ksh ($130) per month, a business owner may make upwards of 60,000 Ksh ($800) per month (Mumbi 2009). Grid electricity is available throughout the town with few residents lacking access to electricity and service being more reliable and consistent than in Maai Mahiu (Mumbi 2009).

[16] The reported populations size of Nakuru corresponds to data gathered from the most recent country census conducted in 1999. More recent population size estimates are around 300,000 (Mumbi 2009).

Figure 7 Map of Kenya with marked field site locations Maai Mahiu (yellow star) and Nakuru (red star).[17]

Night Watchmen

Towns that serve as an overnight stopping point for lorry truck drivers generally have crews of night watchmen that provide security while drivers sleep. The night watchmen surveys for this study took place in the small truck stop town of Maai Mahiu, where a concentration of self-employed night watchmen resides. The watchmen I

[17] The map of Kenya was sourced from http://www.africawithin.com/tour/kenya/maps_of_kenya.htm.

interviewed reported that they direct and monitor lorry trucks in work shifts that last from 7 pm to 7 am, seven days per week. Each watchman surveyed owned at least one flashlight that was used on a nightly basis. All of the watchmen participants were male with an average monthly income between 3500-4000 Ksh, approximately $46-52.

Bicycle Taxi Drivers

In some of Kenya's towns, bicycle taxis provide "for hire" transportation services to the general public within town limits. Known by locals as *Boda Boda* riders, the service originated along the Ugandan-Kenyan border in the 1960's and expanded to other areas in the 1980's (Calvo 1994). *Boda Boda* riders operate a man's bicycle with a padded cushion fitted over the rear rack allowing passengers to ride comfortably. Operators are typically between 18 to 30 years old and are generally school dropouts with limited possibilities of being employed otherwise (Calvo 1994). Bicycle taxi drivers that I surveyed indicated that they operate primarily between the hours of 5 am and 2 am. I focused on surveying drivers that worked during the evening hours (anytime between 6 pm and 2 am). The operators use flashlights mounted on the frames of their bicycles seven nights per week. The Bicycle Taxi Driver surveys took place in Nakuru where bicycle taxis are common. All of the Bicycle Taxi Driver participants were male and had an average monthly income of 9800 Ksh, approximately $130.

Households

The surveys of households took place in Maai Mahiu with members of off-grid households. The average number of members per household in Kenya is five (Kieyah and Nyaga 2008). The reported household sizes of those participating in my study averaged a household size of five. Specific monthly earnings were not ascertained for the household participants, however, based on previous research in the area, the average monthly income for households in this area is around 5000 Ksh, or about $65. The households participating in this study lived in homes made from a range of materials. Households with a higher income tended to build their homes using stone blocks and cement while lower income households utilized a compilation of rock, sticks, and mud. Both generally used corrugated metal for the roof, though the higher income households tended to insulate their roof and walls to a greater extent than those in the lower income bracket. The majority of the household members participating in the survey were women. This was a result of conducting the surveys during the day when the men tended to work outside of the house while the women performed their daily tasks near the home. Although the households reported using flashlights for shorter periods of time than the night watchmen and bicycle taxi drivers, they did nonetheless use them on a regular basis.

RESULTS & DISCUSSION

This section includes a presentation of the performance testing and field evaluation results and a discussion of the associated findings.

Performance Testing

A summary of the measured results and the associated within model variability is included in Table 2 (see Appendix D for the raw data measurements of each performance indicator for each flashlight sample). The within-model variability for the seven key performance metrics included in the study, depicted here by the coefficient of variation (CV), ranged from minimal (<10%) to very high (>50%). The time required to attain a full charge had the least within-model variability, while color rendering had the most. A comparison of the levels of variability within each model reveals that the model C flashlight had the greatest levels of variability for most of the metrics, while model A frequently had the least.

Table 2 Mean, standard deviation, and coefficient of variation (CV) results for the three flashlight models for each of the performance metrics included in the study. Sample size in indicated in column "n."

Performance Indicator	Flashlight A				Flashlight B				Flashlight C			
	n	**Mean**	Std. Dev	CV	n	**Mean**	Std. Dev	CV	n	**Mean**	Std. Dev	CV
Battery Capacity (mAh)	5	**692**	111	16.0%	5	**408**	53	13.1%	5	**664**	144	21.6%
Time to Attain Full Charge (hr)[18]	4	**16.5**	0.4	2.1%	5	**12.8**	0.4	3.0%	4	**20.3**	0.7	3.6%
Max Initial Illuminance (lux)[19]	5	**313**	28	8.9%	5	**332**	77	23.1%	4	**516**	54	10.5%
Run-Time (hr)[19]	5	**37**	7	19.6%	5	**20**	4	21.5%	4	**36**	14	37.7%
Lighting Service per Charge (lux hours)[19]	5	**2,242**	536	23.9%	5	**1,594**	571	35.8%	4	**3,241**	756	23.3%
Light Distribution: Area containing 90% of total lux (m^2)	5	**0.222**	0.018	8.1%	5	**0.161**	0.017	10.6%	4	**0.186**	0.012	6.5%
Color Rendering Index (°Kelvin)	4	**>20,000**	NA	NA	5	**10,616**	4,311	40.6%	4	**14,167**	7,356	51.9%

[18] Test performed after the flashlights received a full charge from the grid charge simulator.
[19] Test performed after the flashlight received a full charge from the Cadex 7400 battery analyzer.

Across models, there was also a significant difference in the mean values for nearly all of the performance metrics ($p \ll 0.05$). The exception to this trend was in the case of color rendering ($p = 0.20$) (Table 3). Tukey's pair-wise comparison and Bonferonni confidence intervals were used to test whether the differences were statistically significant and also to confirm the directionality of those differences.

Table 3 Results for statistical tests to determine if there were verifiable differences in performance between flashlight models. One-way ANOVA was used to assess all differences except in the case of color rendering. For the color rendering comparison the equal-variance assumption was not met and therefore the Kruskal Wallis test was utilized. When the null hypothesis of equality was rejected for each of the metrics, Tukey's multiple comparison test was used to assess differences among pairs of models. The results of the multiple comparison tests are shown in the last column. Models are ordered from smallest to largest in sample mean, and the underline indicates no significant difference (A=Flashlight A, B=Flashlight B, C=Flashlight C).

Performance Indicator	F-statistic	P-value	Tukey's
Battery Capacity (mAh)	5.68	0.018	B $\underline{\text{A C}}$
Time to Attain Full Charge (hr)[20]	259.24	0.000	B A C
Max Initial Illuminance (lux)[21]	16.8	0.000	$\underline{\text{B A}}$ C
Run-Time (hr)[21]	5.74	0.020	B $\underline{\text{A C}}$
Lighting Service per Charge (lux hour)[21]	7.98	0.007	$\underline{\text{A B}}$ C
Light Distribution: Area containing 90% of Total Lux (m^2)	34.43	0.000	A B C
Color Rendering Index (°Kelvin)	--	0.200	$\underline{\text{ABC}}$

[20] Test performed after the flashlights received a fully charge from the grid charge simulator.
[21] Test performed after the flashlights received a fully charge from the Cadex 7400 battery analyzer.

A comparison between the manufacturer's rated specifications and my group's measured values confirms that the flashlights did not perform as advertised with respect to *battery capacity* and the *time to attain a full battery charge* ($p \ll 0.05$) (Table 4). Flashlight A performed 30% below its rated battery capacity (advertised at 1000 mAh) and both Flashlight B and Flashlight C performed 49% below their rated capacities (advertised at 800 mAh and 1300 mAh, respectively) (Figure 8). The *total time required to attain a full charge* varied minimally within each model. However, a comparison between the models indicates that Flashlight B took about 29% less time to charge than Flashlight A and about 41% less time than Flashlight C. Flashlight A took about 19% less time to fully charge than Flashlight C (Figure 9). In all cases, the measured time to charge was higher than the manufacturer's specifications at the 95% confidence level. It is important to note, though, that in the case of Flashlights A and B the difference between advertised levels and measured values, while statistically significant, was modest. Manufacturer's specifications were not available for the other performance indicators measured in the study.

Table 4 Results for statistical tests to determine if the measured performance for each model differed significantly from the manufacturer's advertised specifications for battery capacity and the time required for a full charge.

Performance Indicator	Model	T-statistic	P-value
Battery Capacity (mAh)	Flashlight A	-6.2	0.003
	Flashlight B	-16.5	0.000
	Flashlight C	-9.9	0.001
Time to Attain Full Charge (hr)	Flashlight A	9.6	0.001
	Flashlight B	4.5	0.011
	Flashlight C	15.9	0.000

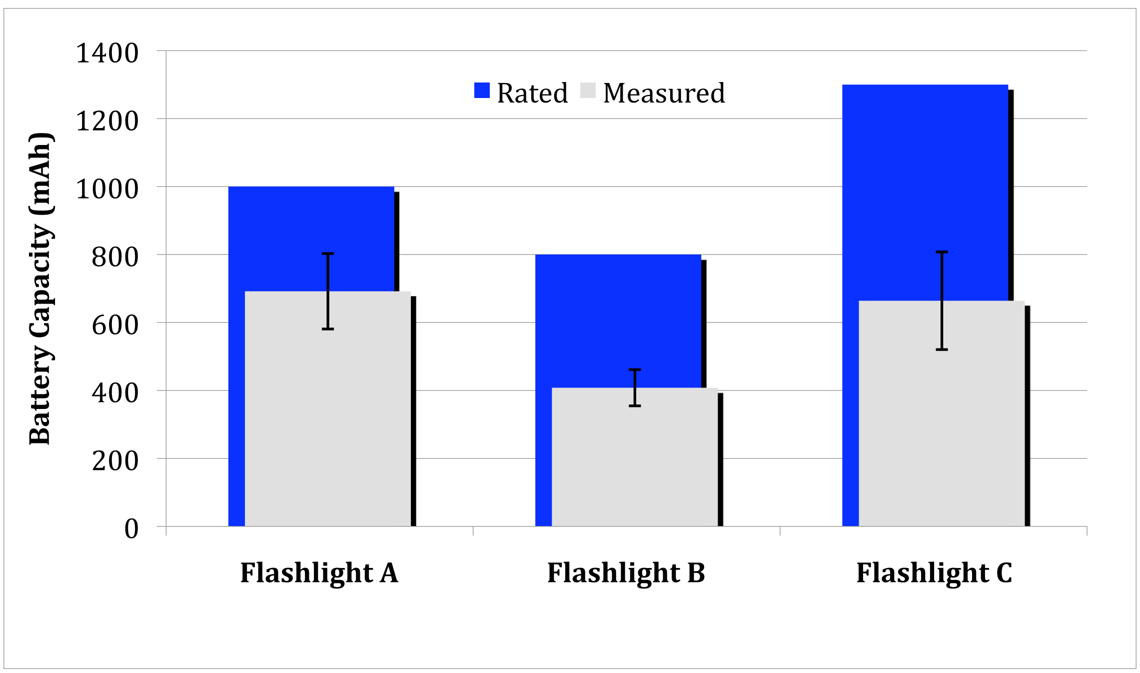


Figure 8 Manufacturers rated battery capacity (blue) in comparison to measured battery capacity (grey). The black error bar lines indicate the 95% confidence interval around the mean measured value.

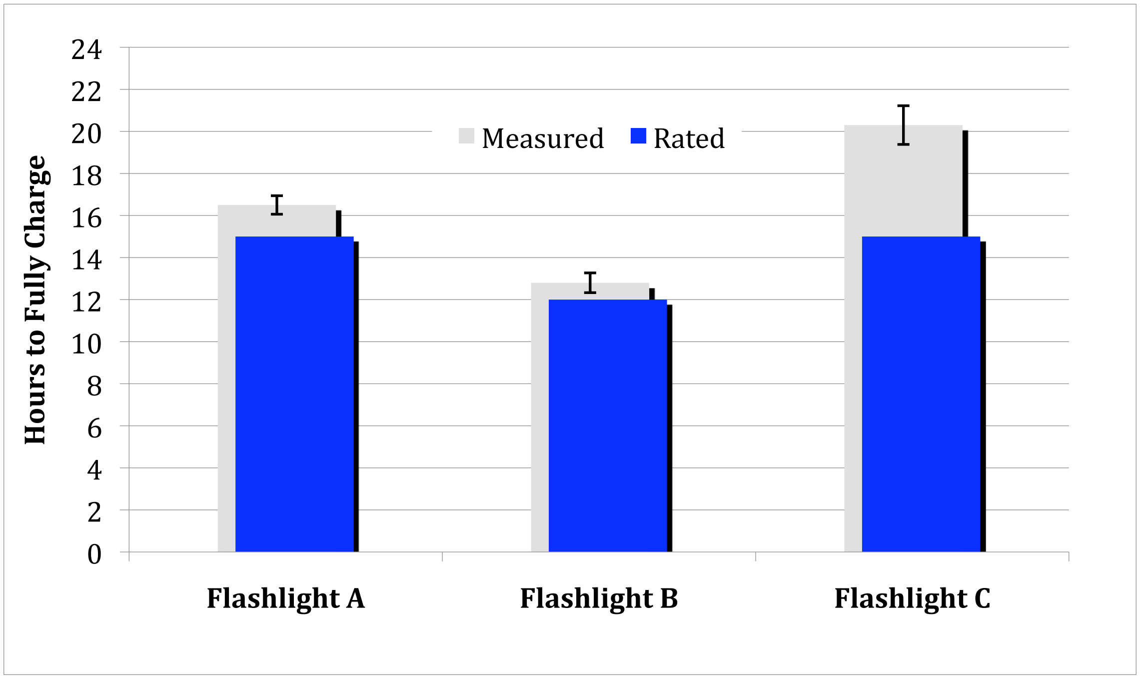


Figure 9 Time required for a full charge. The rated values for each flashlight are shown in blue, while the measured values are shown in grey. The black error bar lines indicate the 95% confidence interval around the mean measured value.

The *maximum initial illuminance (lux)* varied moderately within all three models, though the coefficient of variation was about 13% greater for Flashlight B. A comparison between the models indicates that Flashlight C outperformed the others in terms of initial maximum illuminance, providing light that was 35-40% brighter than the other two models (Figure 10). The *run-time* on a fully charged battery also had moderate within-model variation for Flashlight A and Flashlight B. The within model variation for Flashlight C was somewhat greater. A cross model comparison indicates little difference between models A and C, but the run time for Flashlight B was significantly lower. The lighting service from a fully charged flashlight, measured in *total lux hours,* varied moderately within each model (Figure 11). The differences among the three models were more substantial. The lighting service from flashlight C was higher than that for the other three models by approximately 46%. Flashlight models A and C provided approximately 36.5 hours of “useable” light on average, where “useable” means that the illuminance at one meter exceeded 5.0 lux. Using the same definitions, Flashlight B delivered only 20 hours of usable light from a fully charged battery.

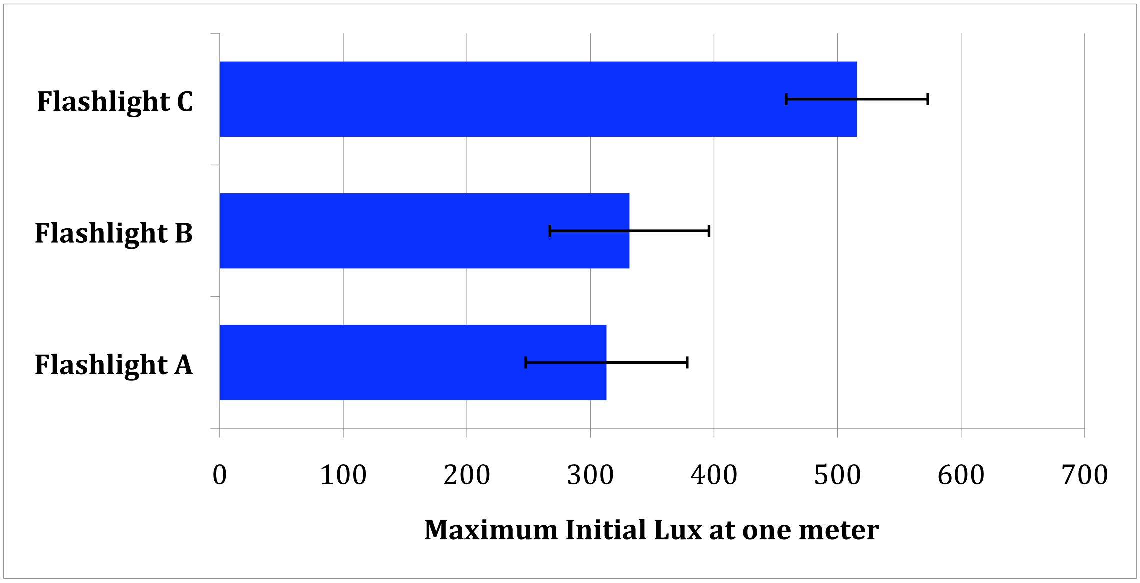
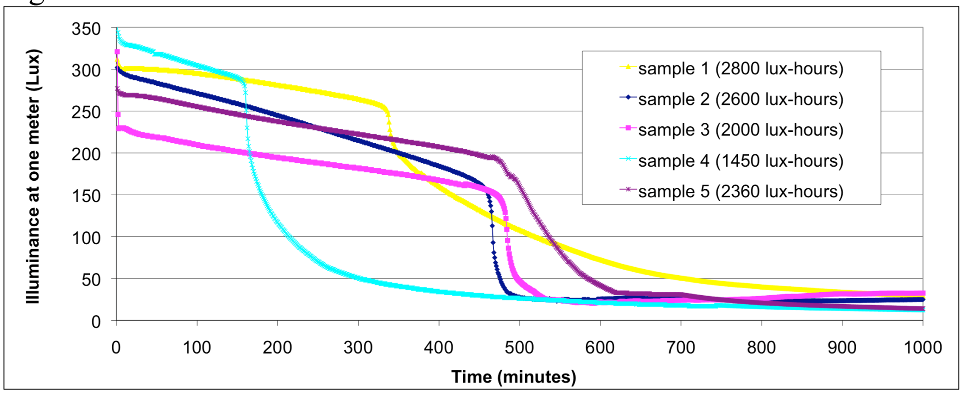
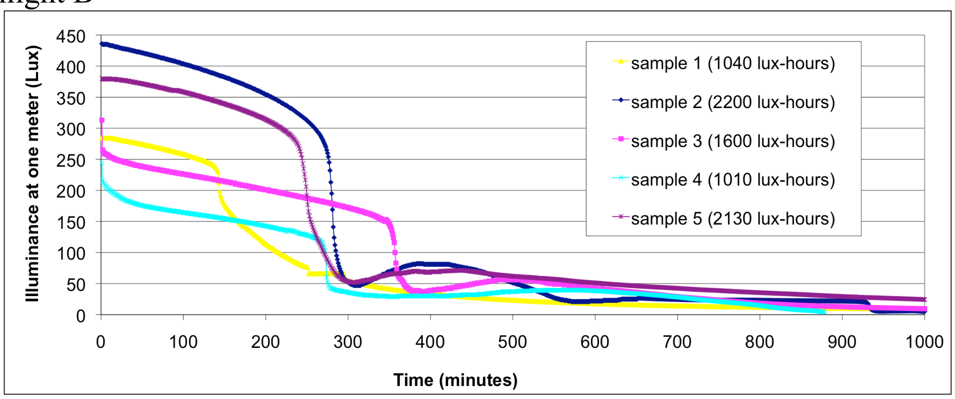


Figure 10 The maximum initial illuminance at a distance of one meter for all three flashlight models. Of the three models, Flashlight C is the brightest and Flashlight A and B are essentially the same. The black error bar lines indicate the 95% confidence interval around the mean value.

A. Flashlight A



B. Flashlight B



C. Flashlight C

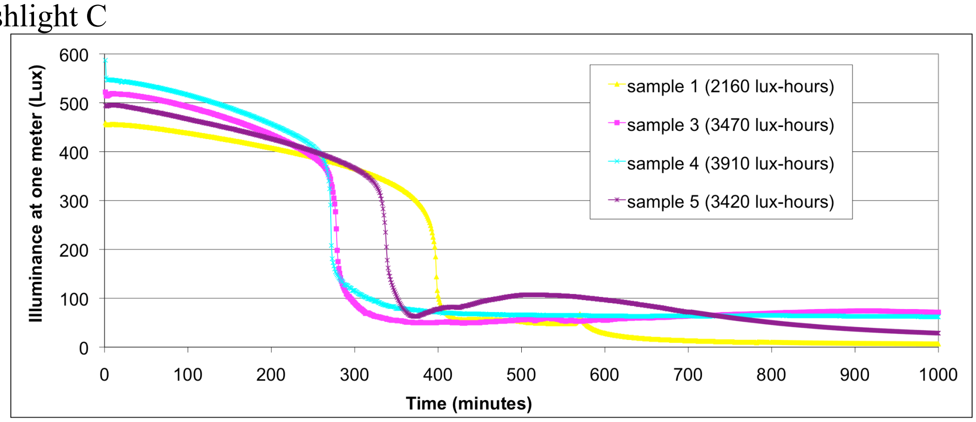


Figure 11 Graphs generated from the lamp discharge test showing the illuminance at a distance of one meter over run-time (complete when illuminance reached 5 lux) for flashlights that start with a fully charged battery. Total measured lighting service in lux-hours for each flashlight is in parentheses. Note that one sample from the Flashlight C model malfunctioned and was not included in the test. The variability within each model for maximum initial illuminance at one meter (lux) can be seen on the left axis where the discharge line begins. Variability can also be seen for the total lighting service, measured in lux hours, by the difference in the area under the discharge line.

The *light distribution* within each model varied minimally. Flashlight A had the least focused beam among the three models. In this case, 90% of its total illuminance at one meter fell within 0.22 m^2 of the center beam. Flashlight B had the most focused beam, with 90% of its total illuminance at one meter falling within 0.16 m^2 of the center beam, while Flashlight C fell in between (0.19 m^2) (Figure 12). The *correlated color temperature* (CCT) varied substantially within each model. Because of this high variability, the CCT measurements did not indicate a significant difference across the 3 models. All models delivered a light color that falls in the blue range (Figure 13).

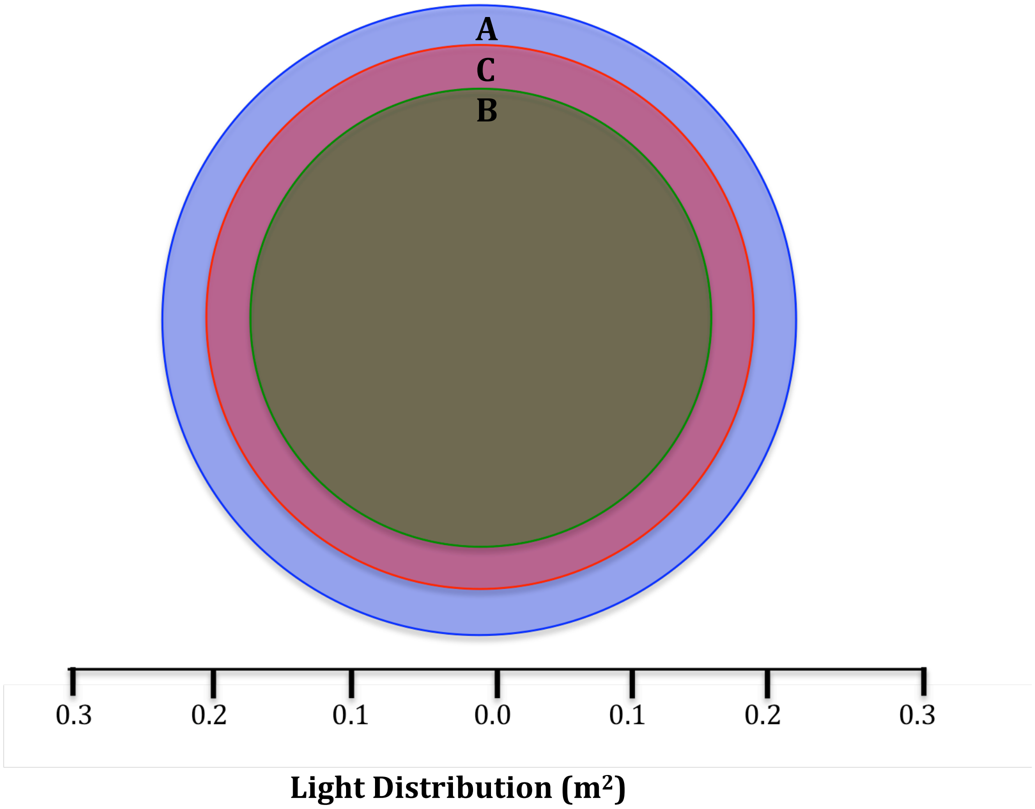


Figure 12 The light distribution measured at a distance of one meter for all three flashlight models. The size of area (m^2) containing 90% of the total illuminance measured over one square meter is smallest for Flashlight B (green), and largest for Flashlight A (blue). In other words, Flashlight B has the most focused beam while Flashlight A has the least focused beam.

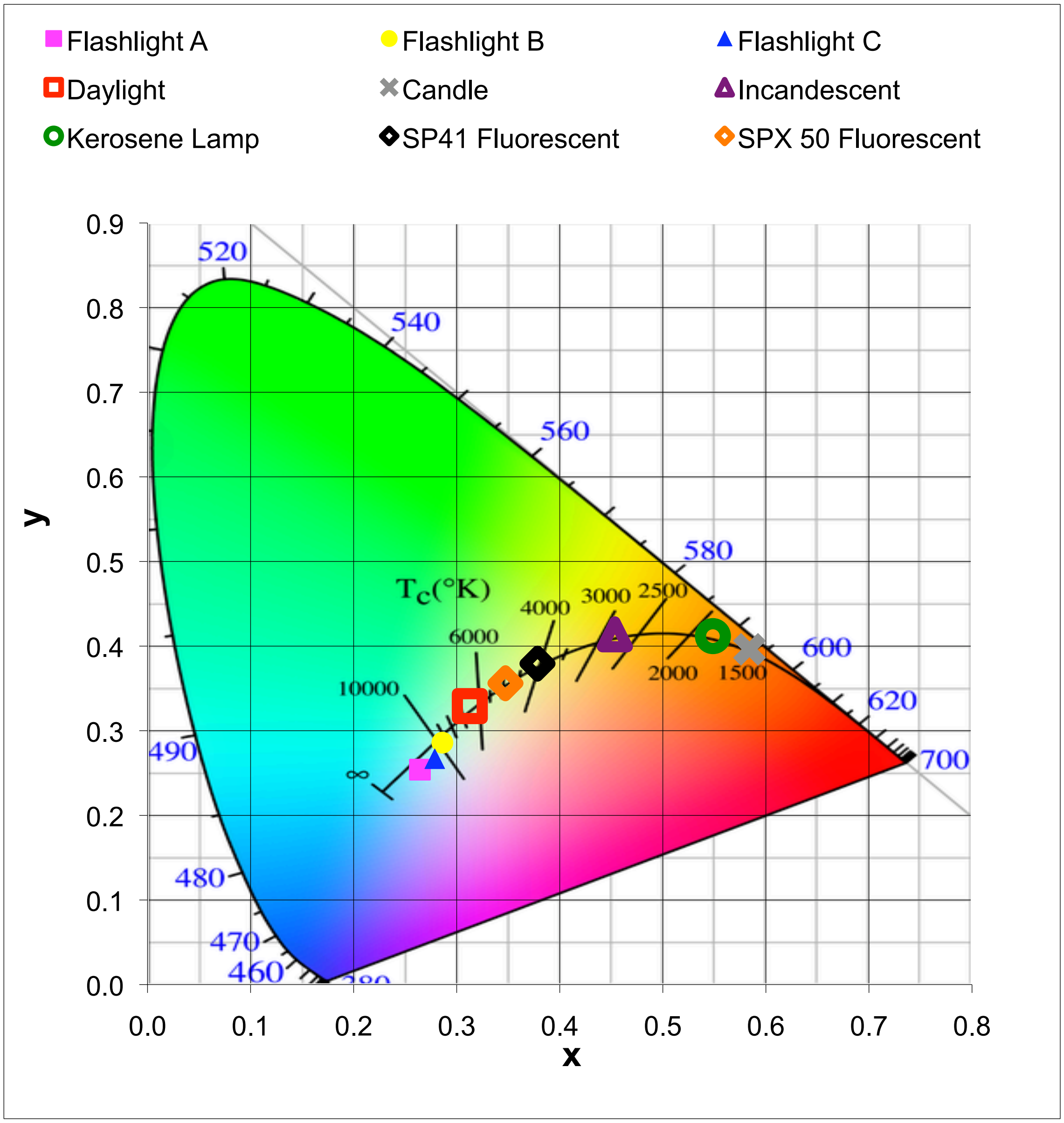


Figure 13 Correlated color temperature (CCT) and color rendering index (CRI) values for the three LED flashlight models as well as several other reference light sources. Flashlight A is indicated by the pink square, Flashlight B by the yellow circle, and Flashlight C by the blue triangle. Other light sources shown include daylight (red hollow square), two types of fluorescent lamps (black and orange diamonds), incandescent lamp (purple hollow triangle), kerosene lamp (green hollow circle), and candle light (grey X). Note that all three LED flashlights fall within the area that is considered to be bluish colored light.

In addition to the above analyses, a final correlation was run across data from all performance indicators for each of the 15 samples. Eight pairs of tests had a significant positive correlation (p-values <<0.05) (Table 5). Battery capacity and the time required to attain a full charge correlate to no surprise; the more ampere-hours a battery can hold, the more amperes it can receive after being fully discharged, and in turn, the longer the recharge process will take at a set voltage. The correlation between time to attain a full charge and run-time, as well as the time to attain a full charge and lighting service per charge, are also expected due to the same relationship to ampere-capacity as just mentioned. Lighting service per charge and run-time correlate because lighting service per charge is a function of the run-time. The four other correlations observed are less expected because the correlating performance indicators are not a direct function of each other, as in the first four correlations. Time to attain a full charge and maximum initial illuminance correlated; first I figured it was because the higher ampere-capacity batteries, which require a longer time to charge, featured more LEDs, thus providing more illuminance. This turned out not to be the case, the flashlight with the fewest LEDs was not the flashlight with the lowest battery capacity. Although the statistics indicate a significant positive correlation, the variability among the maximum initial illuminance values of the samples that required the least amount of time to charge (Flashlight B samples) is likely confounding the correlation (Figure 14). The correlation observed between maximum initial illuminance and lighting service per charge indicates that the flashlights, which provide a greater light output initially, do not discharge at a significantly faster rate than the flashlights with the lower maximum initial illuminance.

The three lamp discharge graphs in Figure 11 show this as well. Lastly, run-time and light distribution, as well as battery capacity and light distribution, also had positive correlations. Light distribution is a factor of how the LEDs within the flashlight are oriented and have no relationship to factors involved in determining run-time and battery capacity, these correlation appear to have occurred just by chance.

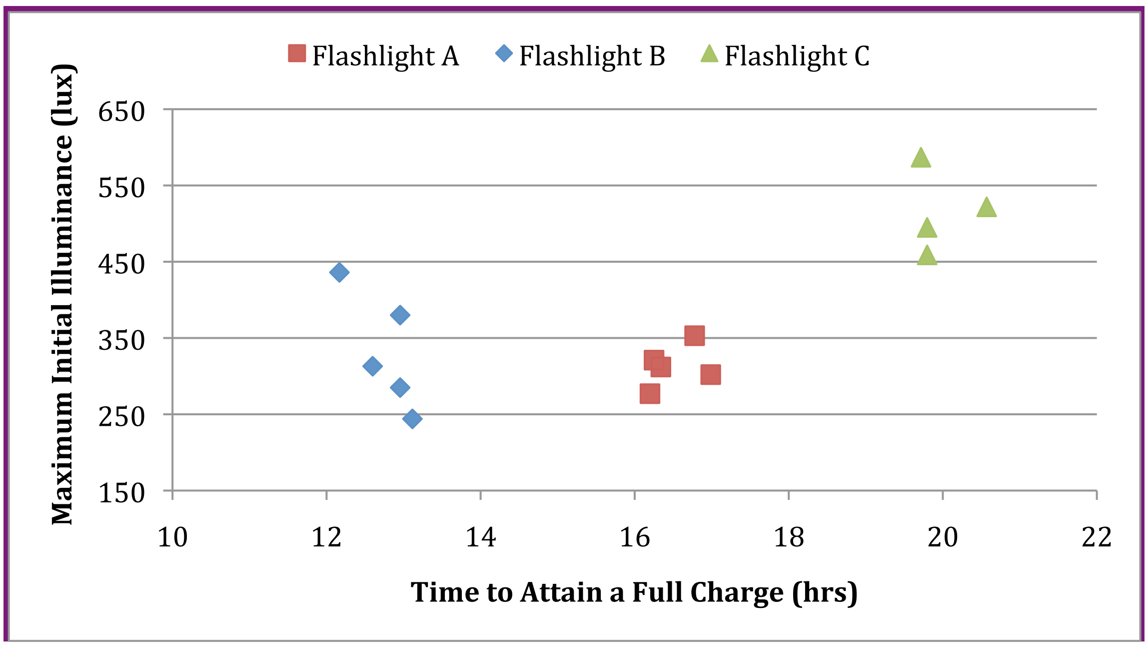


Figure 14 Correlation of maximum initial illuminance and time to attain a full charge. Each marker represents a single flashlight sample. Flashlight B samples (blue diamonds) show a higher degree of variability among the measured maximum initial illuminance. This variability might be confounding the correlation.

Table 5. Pearson correlation coefficients (top value) and corresponding p-value (bottom value) at a 5% significance level across all performance indicators. Values highlighted in red have a significant positive correlation.

	Battery Capacity (mAh)	Time to Attain Full Charge (hr)	Max Initial Illuminance (lux)	Run-Time (hr)	Lighting Service per Charge (lux hours)	Light Distribution: Area containing 90% of total lux (m^2)
Time to Attain Full Charge (hr)	0.632 0.02					
Max Initial Illuminance (lux)	0.062 0.842	0.657 0.011				
Run-Time (hr)	0.315 0.295	0.622 0.017	0.336 0.24			
Lighting Service per Charge (lux hours)	0.312 0.299	0.739 0.003	0.771 0.001	0.731 0.003		
Light Distribution: Area containing 90% of total lux (m^2)	0.624 0.023	0.391 0.167	-0.032 0.915	0.712 0.004	0.467 0.092	
Color Rendering Index (°K)	0.508 0.077	0.285 0.346	-0.128 0.677	0.156 0.611	0.019 0.952	0.334 0.265

Concerns about quality and performance notwithstanding, the type of information presented here can be used to compare the performance of rechargeable flashlights as well as other similar lighting products. Different buyers may have different preferences with respect to the various performance metrics, and these will govern their choices. For example, a buyer who wished to purchase the brightest flashlight (in terms of initial illuminance at a distance of one meter) might choose Flashlight C, while someone who wanted a flashlight with a relatively long run-time could choose either Flashlight A or C. Buyers wishing to select among these three models based on other parameters might consider the following:

1. Flashlight A had the battery with the largest capacity in mAh; this flashlight also had batteries that performed closest to their advertised values.
2. Flashlight C delivered the most lighting service per charge as measured in lux-hours at a distance of one meter.
3. Flashlight B had the most focused light while flashlight A had the least focused light.
4. All three flashlights had light that was fairly blue in color.
5. Flashlight B took the least time to charge, although all three flashlights took considerably more than eight hours to receive a full charge.

Field Evaluation

Field evaluation results and discussion are divided into six sections, prevalence of flashlights, use patterns, common complaints, cost analysis, user preferences for an improved flashlight, and health and environmental implications.

Prevalence of Flashlight

Four types of flashlights were reported to be in use by the survey participants (Figure 15): LED flashlights powered by a rechargeable sealed lead-acid (SLA) battery, LED flashlights powered by dry cell batteries, incandescent flashlights powered by a rechargeable SLA battery, and incandescent flashlights powered by dry cell batteries (Figure 16, Figure 17, Figure 18 and Figure 19).

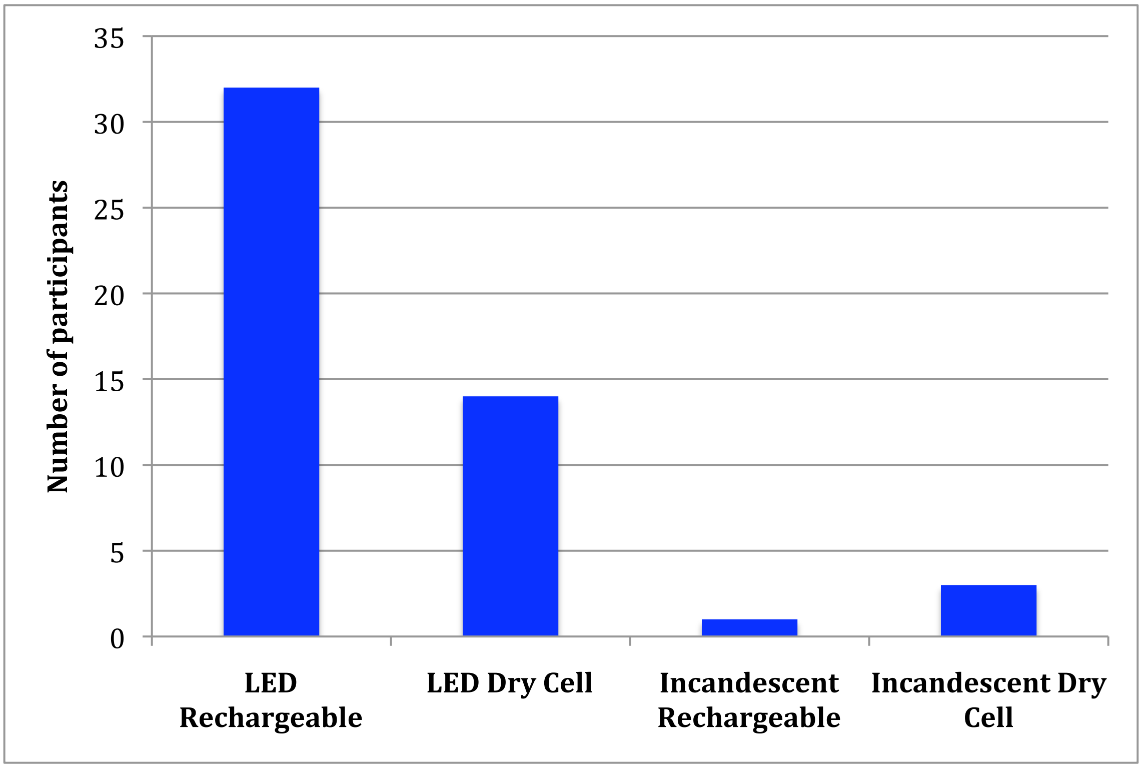


Figure 15 Reported types and quantities of flashlights owned by participants.

LED flashlights have recently permeated the market and appear to be replacing incandescent bulb flashlights that used dry cell batteries (Johnstone et al. 2009). LED technology generally provides efficiency and performance benefits relative to incandescent bulbs, and low cost LEDs have achieved price levels that make them cost competitive with conventional lighting sources for a number of applications (Mills 2005). Rechargeable SLA batteries are also becoming more prevalent, although people with limited access to grid electricity still rely on dry cell battery technology. Flashlights using rechargeable SLA batteries tend to be less expensive to operate over a two-year period than a flashlight using dry cell batteries (Radecsky 2009). The overall price paid for flashlights used by the participants ranged from 80 to 480 Ksh ($1 to $6). Rechargeable LED flashlight prices ranged from 130 to 280 Ksh ($1.70 to $3.70) and dry cell LED flashlight prices ranged from 80-480 Ksh ($1.05 to $6.30). Price generally reflects the number of LEDs; the 80 Ksh flashlight had three LEDs while the 480 Ksh flashlight had ten. For the incandescent bulb flashlights, the two dry cell ones were priced at 100 and 120 Ksh ($1.30 to $1.60), whereas the only reported rechargeable incandescent flashlight was actually purchased as a rechargeable LED flashlight (when the LED no longer worked the owner replaced it with an incandescent bulb). In addition to the initial cost of the flashlights, users must pay ongoing costs associated with recharging or buying replacement dry cell batteries. The average cost reported to recharge the SLA batteries in flashlights was 20 Ksh ($0.26) and the average cost reported to purchase one dry cell battery was 30 Ksh ($0.40); note that approximately 80% of flashlights using dry cell batteries required two batteries. The total cost of ownership (over the product lifetime) is dominated by the cost of replacement batteries or charging fees (Mills and Jacobson 2008).

Figure 16 Rechargeable LED flashlights owned by the night watchmen.

Figure 17 Dry Cell LED flashlights owned by a household participant.

Figure 18 Rechargeable incandescent flashlight used by a household participant.

Figure 19 Dry cell incandescent flashlight used by a household participant.

The majority, 64%, of flashlights used as reported by survey participants, were rechargeable LED flashlights (Figure 20). LED flashlights powered by dry cell batteries were the next most common, comprising over one-fourth of the flashlights used. Incandescent bulb flashlights that used either rechargeable or dry cell batteries were used by less than 10% of those surveyed. When the data are broken down on a per group basis, it is interesting to note that only the household participants used incandescent bulb flashlights. Three of the watchmen did report using LED flashlights with dry cell batteries, but most of the dry cell torches were found in households (82%). The households use flashlights with dry cell batteries to a greater extent than flashlights with rechargeable batteries. While the size of my sample is too small to draw firm conclusions, this may represent a conscious choice related to the fact that the household members that I interviewed lived further from grid electricity than the other respondents. Living further from the grid made use of a rechargeable flashlight less convenient. All three groups used LED flashlights with rechargeable batteries, but the bicycle taxi driver's are the only group that used that type exclusively. This may be because the drivers are based in a larger town where rechargeable LED flashlights are more readily available than the other types.

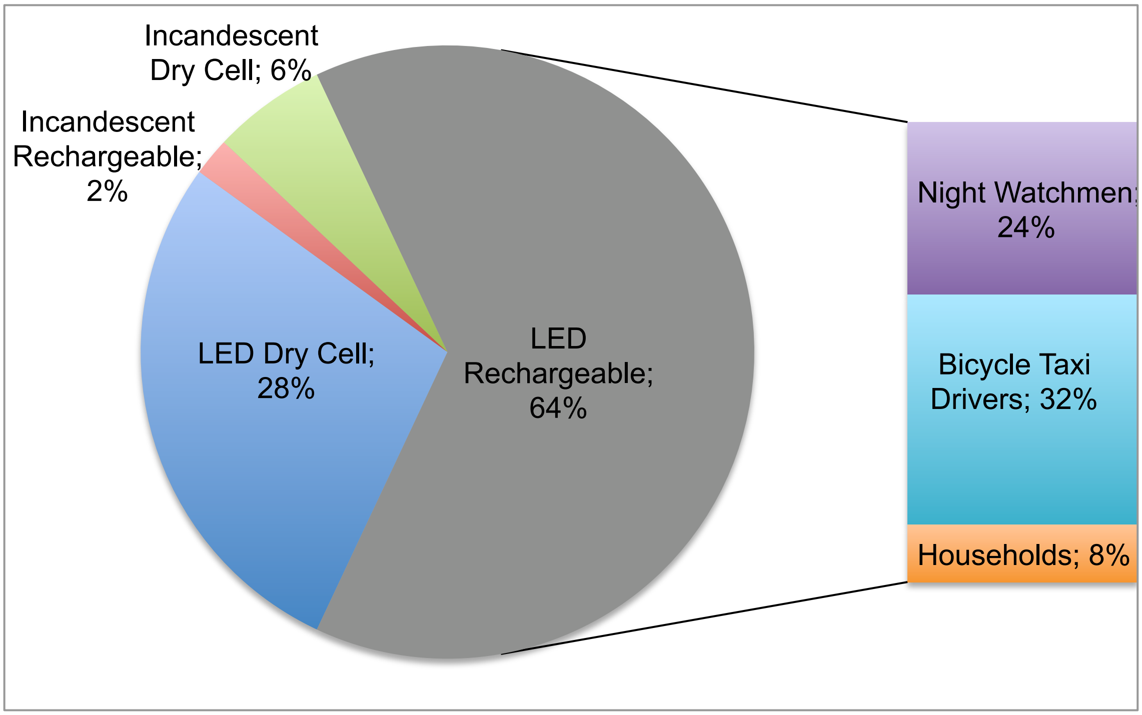


Figure 20 Four types of flashlights reported to be in use by the study participants. LED flashlights powered by rechargeable sealed lead-acid batteries are the most popular choice followed by dry cell battery powered LED flashlights. Incandescent bulb flashlights are the least common. Of the LED rechargeable flashlights, bicycle taxi drivers owned a greater percentage, while households owned the least.

Use Patterns

Use patterns are explained under four categories: flashlight applications, frequency of use, time of use, and frequency of charging or replacing batteries. Supplementing use pattern data reported on the survey, results from the dataloggers embedded in seven of the night watchmen's torches are also reported in the time of use section (see Appendix E for a more detailed account of that trial).

Flashlight Applications. Both the night watchmen and the bicycle taxi drivers use flashlights for their jobs; flashlight uses outside of their employment were not ascertained. Household flashlight users reported using flashlights under four circumstances: going outside at night, in the bedroom at night, in the kitchen at night, and when searching for something inside the house. The most commonly reported use by households was for going outside at night, which was cited by 15 out of the 16 participants. Going outside at night includes walking between town and home, using the outside toilet, opening gates for animals, and other tasks which require going outside in the dark. Seven households reported using their flashlight in the bedroom at night; this includes getting ready for bed and assisting the children to prepare themselves for school in the early morning. Five households reported using the flashlight to search for items inside the house during the day or at night, whenever lighting levels were too dim to locate the item of interest. Two out of the sixteen households reported using the flashlight while cooking at night (Figure 21).

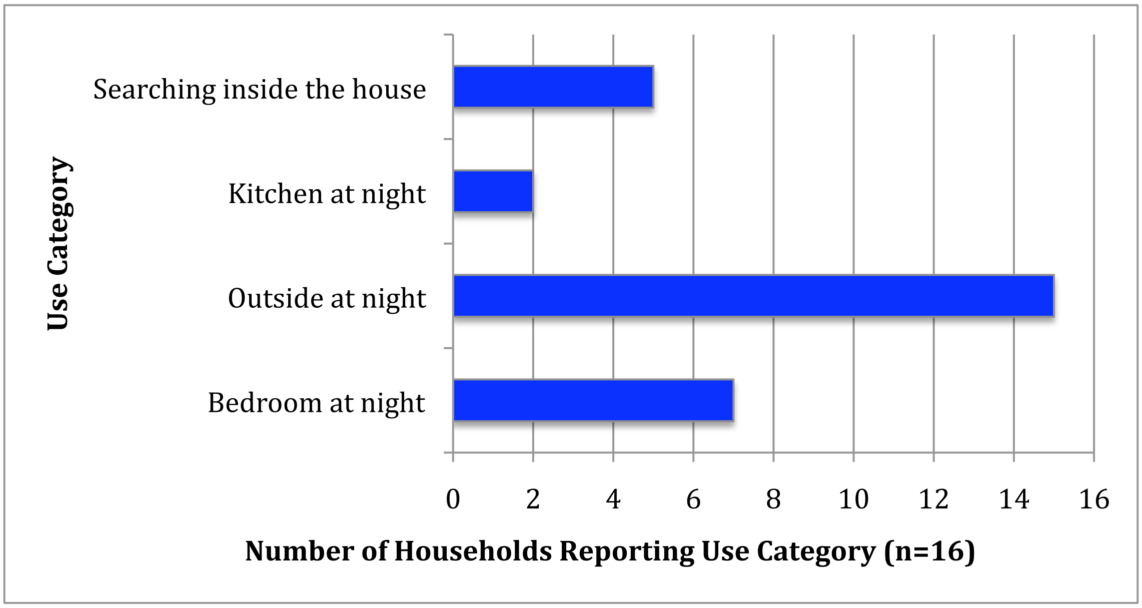


Figure 21 Common reported uses of flashlights in homes. Each household reported multiple uses.

Frequency of Use. Both night watchmen and the bicycle taxi drivers use their flashlights on a daily basis during the night hours and regularly work seven days a week. On average households used flashlights less frequently than the night watchmen or the bicycle taxi drivers. Among the sixteen households, participants reported last using their flashlight within two days, while 46% of households reported using their flashlight the previous evening.

Time of Use. The flashlight is a critical device for both the night watchmen and bicycle taxi drivers. It enables them to safely and effectively work through the night. Because both groups use the flashlight on a daily basis while on the job, the amount of time they have the light turned on is substantially greater than in the case of households. Night watchmen and bicycle taxi drivers reported using their flashlights on a nightly basis for roughly the same amount of time, averaging 3.5 hours and 3.75 hours respectively. Households, in contrast, reported using their flashlight on average for only 18 minutes per day (Figure 22).

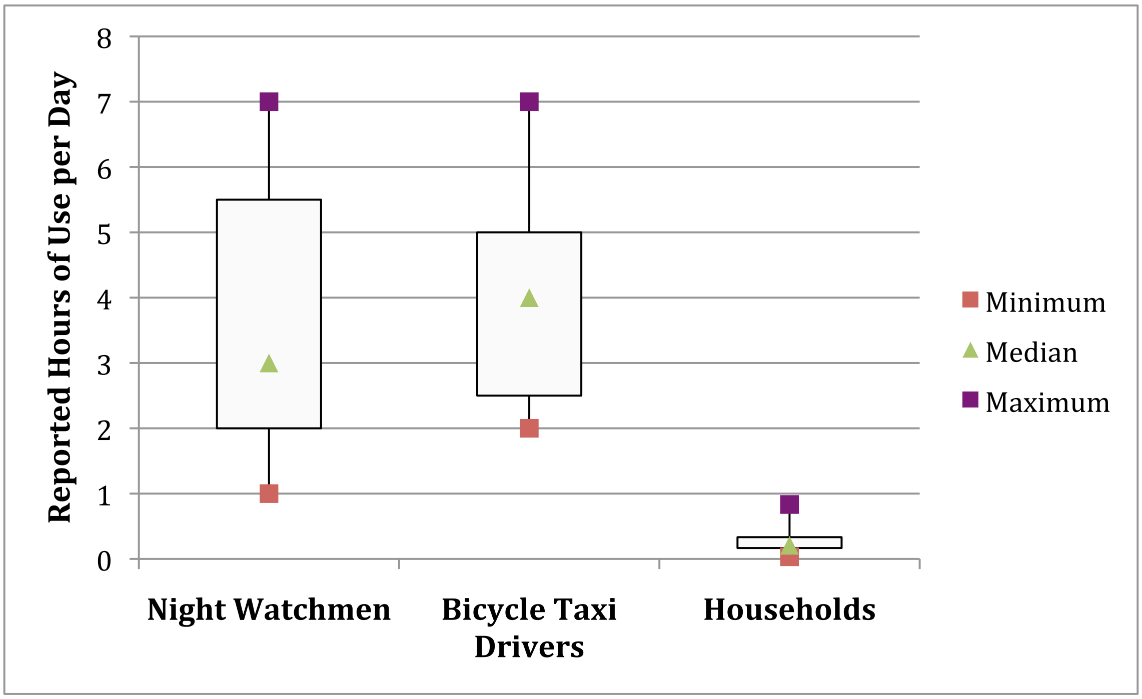


Figure 22 Box plot of the number of hours per day flashlights are used as reported by the three groups.

Data from the dataloggers integrated into seven flashlights, and then given to the night watchmen to use as normal, indicate that on a nightly basis the night watchmen use the flashlight for an average of 53 minutes during their 12-hour shift. Among the seven watchmen this varied from 30 minutes to 4.5 hours per night. On the survey the night watchmen indicated that they used their flashlights for 3.5 hours on average per night. The discrepancy between the reported value and the value recorded by the datalogger is likely due to the difficulty on the part of the night watchmen in assessing actual time of use. Over a twelve-hour shift the night watchmen will turn their flashlight on and off frequently as lorry trucks pull in to park. The period of time the watchmen has the flashlight on at any given point is often very short. When asked to reported the amount of time their flashlight was turned on nightly, the watchmen estimated the number of times they typically turned on the light and for how long they thought it was on each time. Under these circumstances, it is reasonable to expect the night watchmen might have difficulty accurately calculating their actual time of use on a nightly basis.

The datalogger trial ran from July until December; however, all but two of the flashlights failed and all of the dataloggers failed before the trial was complete (see Appendix E for a more detailed report of the datalogger trial). Over the roughly 3,600-hour (150 day) trial, all seven flashlights cumulatively recorded 2,016 hours of use. Datalogger-1 recorded the largest number of hours at 960, Datalogger-2 recorded 144 hours, Datalogger-3 recorded 360 hours, Datalogger-4 recorded 144 hours, Datalogger-5 was lost before any data were downloaded, Datalogger-6 recorded 384 hours, and Datalogger-7 recorded only 48 hours.

Frequency of Charging/Replacing Batteries. Fourteen of the 15 night watchmen who used rechargeable flashlights reported recharging their flashlights on a daily basis, whereas the bicycle taxi drivers, all of whom reported using rechargeable flashlights, reported recharging every three days on average. The four households using rechargeable flashlights reported recharging their flashlights every seven days on average, though responses ranged from four to fourteen days.

Fourteen of the households and three of the night watchmen reported using flashlights with disposable dry cell batteries; however, the night watchmen used the dry cell flashlights only as an emergency backup flashlight. None of the bicycle taxi drivers used dry cell battery powered flashlights. The median number of days between dry cell battery replacement was 14 days for the households and around 24 days for the night watchmen.[22] The night watchmen only used the dry cell powered flashlights as an emergency replacement light when their rechargeable flashlight malfunctioned; the lower frequency of dry cell battery replacement as compared to households reflects this use pattern. Note, however, that the since households reported using flashlights for less than 20 minutes per day the dry cell batteries lasted considerably longer than they would if the night watchmen and bicycle taxi drivers used dry cell powered flashlights with regularity. Because the night watchmen and bicycle taxi drivers report using their flashlights for roughly ten times longer than households, they would potentially need to replace batteries in a dry cell LED flashlight every 1.5 days if they used this type of flashlight. The

[22] Only twelve of the seventeen participants using dry cell flashlights were able to report on the frequency with which they replaced their batteries (nine households and three night watchmen). This was either because their spouse, not the person being surveyed, was the purchaser of batteries or they could not remember.

responses from the household respondents indicated that the dry cell batteries in LED flashlights lasted longer (average replacement interval was 30 days) than the dry cell batteries in incandescent flashlights (14 days). This is consistent with the fact that incandescent lights are less efficient and draw a greater amount of power than LED lights.

<u>Common Complaints</u>

A total of 87% of those surveyed reported having problems with their flashlights in the previous six months. The number of night watchmen and household participants reporting problems in the last six months was approximately 20% higher than the rate for bicycle taxi drivers (Figure 23). The reported useful lifetime for flashlights (i.e., the time before they no longer worked) ranged from one week to eighteen months. The median reported flashlight lifespan was two months and the average flashlight lifespan was just over three and a half months (Figure 24).[23] Ninety percent of the forty-one participants reporting on the lifespan of their flashlight said they lasted six months or less (Figure 24). These results suggest severe and widespread quality problems in the Kenyan flashlight market.

[23] Forthcoming calculations estimating the annual cost and quantifying annual waste accumulation and lead disposal are based on the median reported lifespan rather than the mean average reported lifespan. This was done to eliminate outlier effects since the significantly longer reported flashlight lifespans (12 and 18 months) correspond to flashlights used as backup, not typical use patterns.

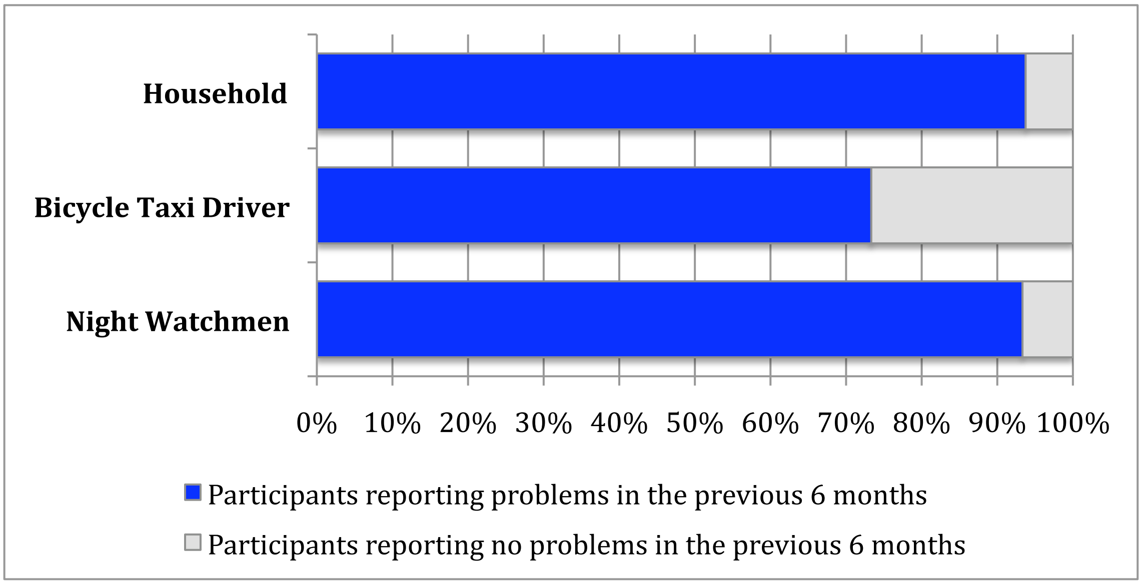


Figure 23 Fraction of 46 survey respondents reporting problems with their flashlights that occurred in the past six months. Overall, 87% of respondents reported having problems.

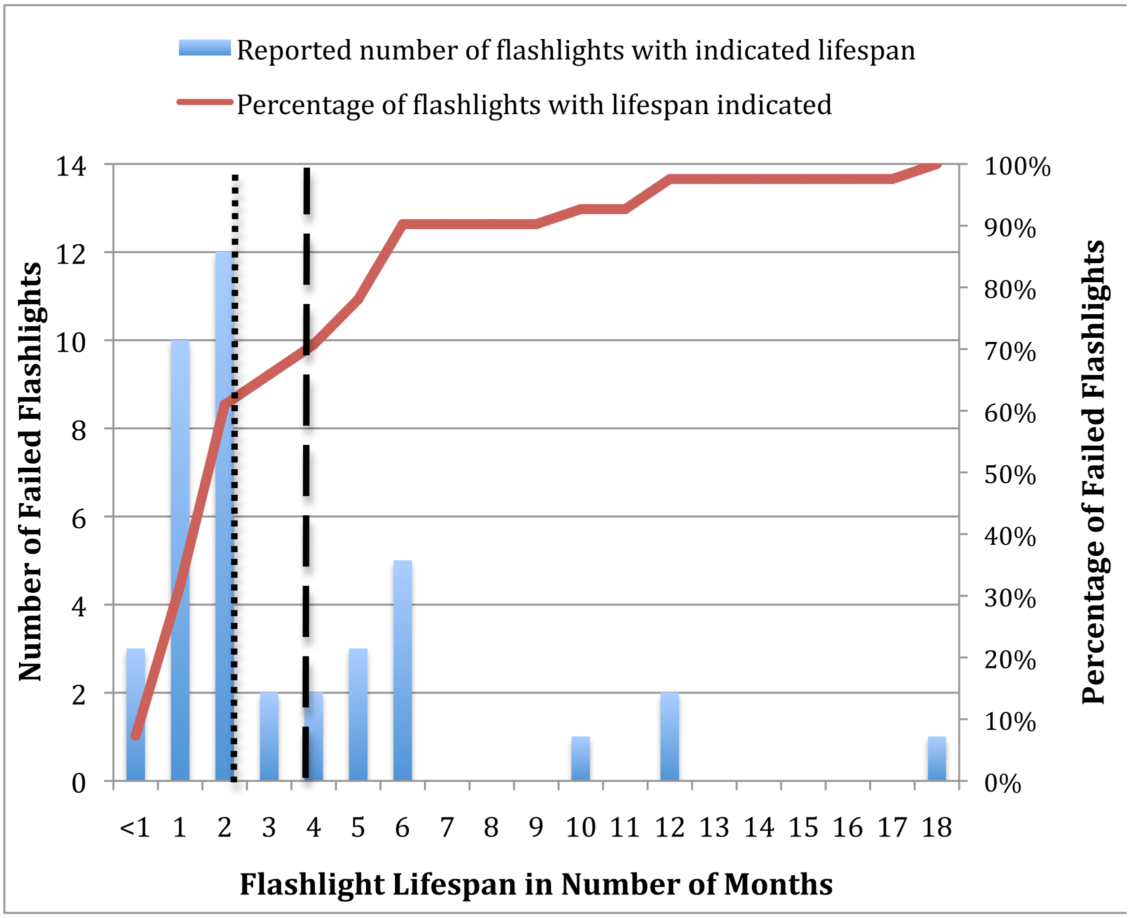


Figure 24. Cumulative probability plot of flashlight lifespan as reported by study participants (red line). Bar graph indicates the number of flashlights with respective lifespan as reported by participants. The dotted line represents the median lifespan and the dashed line represents the mean average reported lifespan.

When asked about their experiences with the flashlights, failure of LEDs[24] was the most common complaint, closely followed by water leakage leading to corrosion and electronic component failure (Figure 25, Appendix B. Photo 9 and Photo 10). Four main categories made up over 75% of the complaints: the two categories mentioned above, the battery was no longer able to maintain a charge (thus requiring more frequent recharging events), and switch failures (likely a result of weak solder joints that break, disconnecting the wire linking the switch to the lighting circuit). Three other categories were less frequently mentioned, though together they compromise approximately 25% of the complaints: dry cell batteries being too expensive to replace, the charging mechanism on the rechargeable flashlights failing to operate, and the flashlight body being so brittle that when it drops it breaks. The three groups emphasized different complaints (Figure 26). LED failure and water leakage were the only complaints reported by all groups. Both bicycle taxi drivers and night watchmen, but not households, complained that dry cell batteries were too expensive and that their current flashlight's rechargeable batteries no longer kept the charge as it had when they first purchased it. Night watchmen were the only ones who complained of the rechargeable charging mechanism failing. Households were the only ones to complain about the switch wires failing. Both households and bicycle taxi drivers complained about how easily the flashlights broke when dropped.

In addition to the problems reported on the survey, the seven night watchmen who participated in the datalogging flashlight trial also reported any problems they

[24] Respondents who indicated that the LEDs in their flashlight had "failed" were referring to the fact that the LEDs ceased delivering light. In many cases, this failure may have been due to a bad wire or solder connection, corrosion on the circuit board, or faults other than actual failure of the light emitting diode itself.

experienced with their flashlight over the 150-day trial. Five of the seven night watchmen reported that the flashlight head broke after being dropped, at which time the LEDs malfunctioned or stopped working entirely (Appendix B. Photo 11 and Photo 12). One night watchman dropped his flashlight, but no problems resulted. And one night watchman reported that his LEDs suddenly stopped working after three months (see Appendix E for a more detailed report of the datalogger trial).

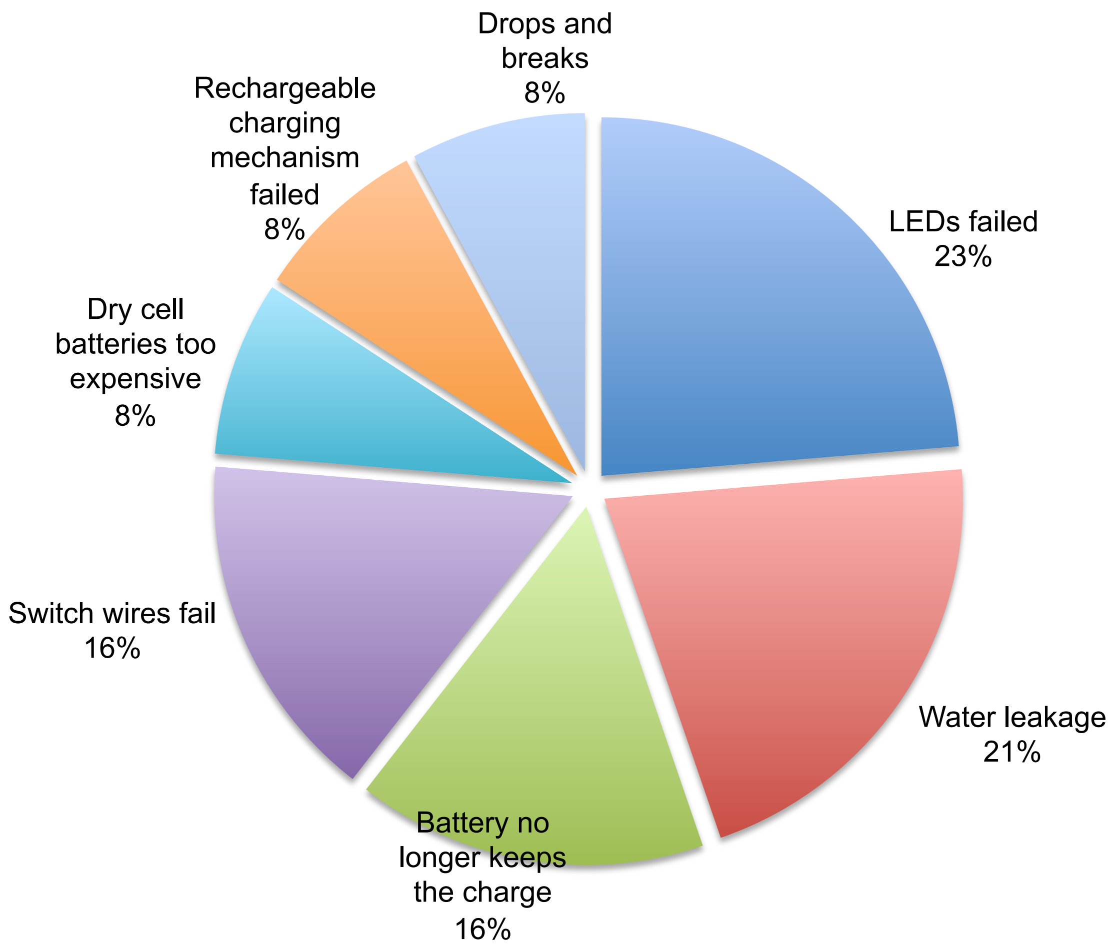


Figure 25 Summary of common problems experienced by 46 flashlight users surveyed in Kenya. Four criticisms regarding flashlight performance by surveyed end-users in Kenya make up 75% of the reported complaints: LEDs failed, water leakage, battery no longer keeps the charge as they initially had, and the switch wires fail.

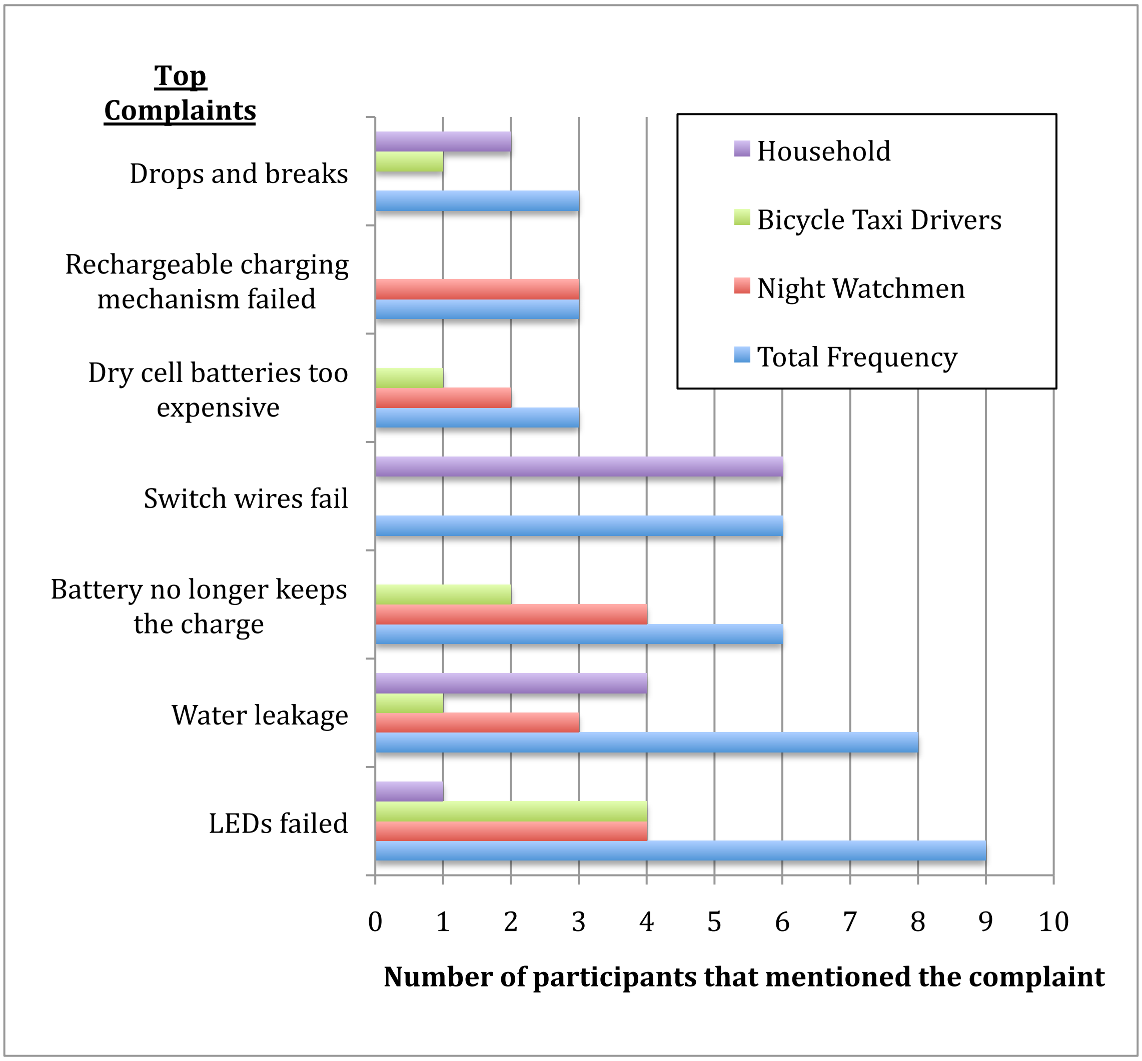


Figure 26 Top complaints broken down by each of the three groups. Total frequency includes all participants within the three groups surveyed. LED failure and water leakage were the only complaints reported by all groups.

The fact that respondents frequently cited rapid LED failure as a problem is particularly worrisome given that many manufacturers market the flashlights with claims that the LEDs will last a very long time compared to incandescent bulbs (e.g., claims of 50,000 or 100,000 hour lifetimes for the LED lights are commonly found on the packaging for these products). In practice, quality control and quality assurance in manufacture of LEDs varies widely, and few – if any – of the LEDs in the flashlights used by the respondents in this study delivered light for more than a few thousand hours. In fact, descriptions of flashlight failure modes suggest that LEDs commonly ceased delivering light after only a few hundred hours of operation. While the cause of the problem may or may not have been related to actual failure of the diode itself, many end-users that I interviewed appeared to interpret the fault as a problem with the LED.

Cost Analysis

Taking account of the prevalence of flashlights types, use patterns, and quality concerns impacting flashlight lifespan as expressed by this study's participants, the annual cost to flashlight users can be estimated. The cost analysis considers the initial cost and the cost to recharge or purchase new batteries, the two primary factors involved in the cost of flashlights. I use this information to estimate the annual cost of owning and operating a flashlight following the user feedback reported by participants.

Initial Cost. The initial cost for the flashlights currently in use by the participants ranged from 80 to 480 Ksh, \$1.05-\$6.30. On average the night watchmen tended to pay more for their flashlights than the bicycle taxi drivers. The households tended to pay the least of the three groups. The night watchmen paid a median price of 175 Ksh ($2.30), the bicycle taxi drivers paid a median price of 150 Ksh ($1.97), and the households paid a median price of 120 Ksh ($1.58). For both the night watchmen and the bicycle taxi drivers the median initial cost was 150 Ksh ($2.00), while the households reported 100 Ksh ($1.30).

The initial cost broken down by flashlight type shows that the most expensive flashlights are the rechargeable LED flashlights and the least expensive are the rechargeable incandescent flashlights (Table 6).

The initial cost of a rechargeable LED flashlight ranged from 130-280 Ksh ($1.70-$3.70) with a median price of 150 Ksh ($2.00). The initial cost of a disposable dry cell LED flashlight ranged from 80-480 Ksh ($1.05-$6.30) with a median price of 110 Ksh ($1.45). The initial cost of a dry cell incandescent flashlight ranged from 100-120 Ksh ($1.30-$1.60), though only two of the three owners of these types of flashlights were able to report the cost. Prices for rechargeable incandescent flashlight are not included because the one flashlight of this type reported was initially purchased as a rechargeable LED and replaced with an incandescent bulb when the LED failed. The reported prices agree with prices documented in a recent off-grid lighting market presence pilot study conducted through the Lighting Africa program (Johnstone et al. 2009) (Table 6). In that report, data from flashlight vendors in three towns of varying population sizes indicate that the respective median prices were 150 Ksh (rechargeable LED flashlights), 100 Ksh (dry cell LED flashlights), and 50 Ksh (incandescent dry cell flashlights). Rechargeable incandescent flashlights, however, were not represented in any of the stores surveyed by Johnstone et al. (2009).

Table 6 Median initial costs for flashlights as reported by Johnstone et al. 2009 and by the three groups participating in the current study. Sample size is indicated in the column "n."

Flashlight Type	**Median Initial Cost (Johnstone et al., 2009)**			**Median Initial Cost (This Study's Participants)**		
	N	Ksh	USD	n[25]	Ksh	USD
LED Rechargeable	141	150	$1.97	27	150	$1.97
LED Dry Cell	100	100	$1.32	10	110	$1.45
Incandescent Dry Cell	30	50	$0.66	2	110[26]	$1.45[26]

[25] The number of participants reporting a price associated with their type of flashlight. In some instances people were not able to report the cost, typically due to the inability to remember or because they were not the purchaser.
[26] Only two people reported a cost for buying an incandescent dry cell flashlight

Cost to Charge/Replace Batteries. Thirty-four participants reported the cost to recharge their rechargeable flashlights. Nineteen of the 34 were able to charge for free either at their work place or at home, while the other 15 respondents took their flashlights to a charge-shop to be charged (Figure 27). Those taking their flashlights to a charge shop paid a median price of 20 Ksh per charge ($0.25); the price ranged from 10-30 Ksh ($0.13-$0.40). There was no substantial difference between the price charge-shops charged between the two towns, Maai Mahiu and Nakuru, and thus all three groups who paid for a charge paid roughly the same. The bicycle taxi drivers, however, tended to charge their flashlights for free more often than did the night watchmen and households (Figure 27). This is likely a result of grid-electricity being more accessible to households in the city than in the small town. However, of the 15 night watchmen, six reported being able to charge for free at their workplace. Eight of the 15 bicycle taxi drivers charged "for free" at their homes,[27] and, of the four households who reported using rechargeable flashlights, only one was able to recharge for free at her workplace.

[27] The amount of metered electricity required to charge these products is extremely small.

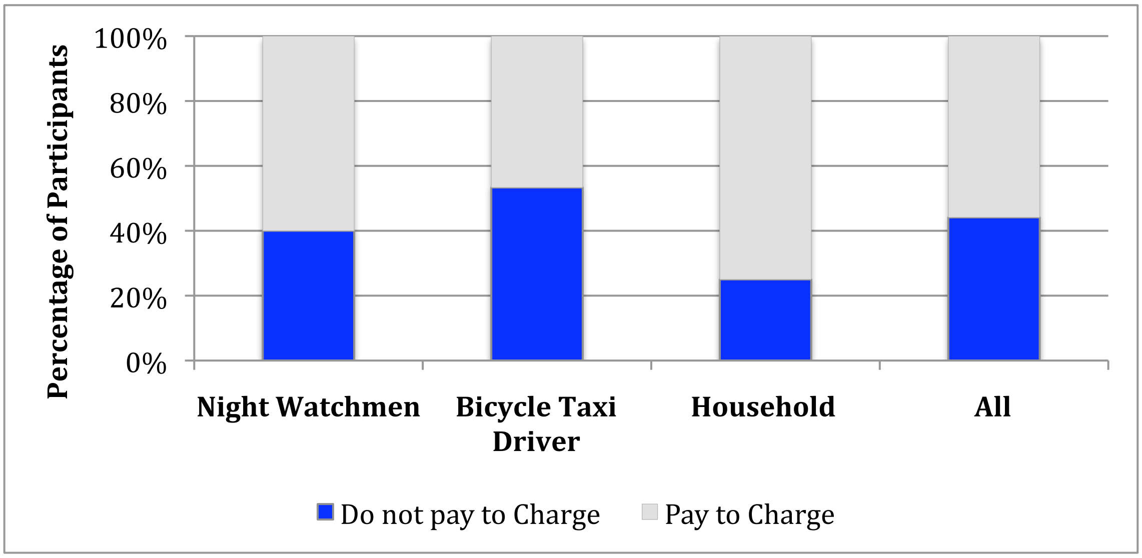


Figure 27 Percentage of participants, broken down by group, who pay and who do not pay to charge their flashlight. The bicycle taxi drivers tend to recharge their flashlights for free more often than the night watchmen or households.

Ten of the participants using flashlights powered by dry cell batteries (two night watchman and eight households) were able to report how much they paid for the batteries, with a median price per battery of 30 Ksh ($0.40). Of those ten, eight used flashlights that required two batteries and the other two participants owned flashlights using just one battery (Appendix B. Photo 13 and Photo 14). Taking into account the number of batteries the flashlight requires, the median price to replace the flashlight batteries is 60 Ksh ($0.79). It is interesting to note that the two participants who owned the single battery flashlights reported paying 20 Ksh ($0.26) for the one battery, but those who had to purchase two batteries reported paying either 60 or 70 Ksh ($0.80, $0.92) for the two batteries. This likely reflects the different quality of batteries purchased, with the lower priced batteries having a smaller Ampere-hour capacity.

<u>One-Year Cost Analysis</u>. This section includes one-year cost estimates for two scenarios. The first scenario involves a high-intensity flashlight use pattern while the second involves a low-intensity flashlight use pattern. Each scenario estimates the annual cost for LED rechargeable, LED dry cell, and incandescent dry cell flashlights. I have also included estimates of hypothetical annual costs under each scenario for an improved quality LED flashlight,[28] and an improved capacity LED dry cell flashlight,[29] if such products were made available. For clarity purposes, I will refer to the three flashlight types that are currently available as *regular* versus the hypothetical *improved* flashlights.[30]

Scenario one depicts high-intensity flashlight use, following the typical use patterns reported by both the night watchmen and the bicycle taxi drivers (Table 7). The high intensity use one-year cost analysis assumes the following:

1. Initial costs: *regular* rechargeable LED flashlight, 150 Ksh: *regular* dry cell LED flashlight, 100 Ksh: *regular* dry cell incandescent flashlight, 50 Ksh; *improved*

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[28] The difference between the regular LED rechargeable flashlight and the improved quality LED rechargeable flashlight is that it lasts for one-year versus two months, and has an initial cost of 600 Ksh, four times as much as the regular LED rechargeable flashlight.

[29] The difference between the regular LED dry cell flashlight and the improved capacity LED dry cell flashlight is that it uses batteries that have 2.5 times the ampere-hour capacity, costing 120 Ksh, twice as much as the regular dry cell batteries, and the initial flashlight cost is 300 Ksh, three times as much as the regular LED dry cell flashlight. Dry cell batteries with 2.5 times more ampere-hour capacity than those commonly used by my participants are widely available in Kenya, however, because of their higher cost they are not commonly used by low-income people, rather they are used primarily by middle and higher income people.

[30] If no distinction is made between *regular* or *improved* it means the stated assumption holds true for both cases.

quality LED rechargeable flashlight, 600 Ksh[31]; *improved* capacity LED dry cell flashlight, 300 Ksh.[32]

2. One *regular* flashlight lasts two months,[33] one *improved* flashlight lasts one year.
3. The cost per grid charge for rechargeable flashlights is 20 Ksh.
4. Rechargeable flashlights are charged every 3 days.
5. Dry cell powered flashlights use 2 batteries.
6. The cost to replace two *regular* dry cell batteries is 60 Ksh, and 120 Ksh for two *improved* capacity dry cell batteries.[34]

Regular dry cell batteries are replaced every 1.5 days in LED flashlights and every 0.75 days in incandescent flashlights,[35] and *improved* capacity dry cell batteries are replaced every 3.75 days.[34]

The second scenario depicts a lower-intensity of flashlight use, following the use patterns reported by households (Table 8). This scenario uses the same assumptions as in the high intensity use scenario except as follows,

1. Rechargeable flashlights are charged every 7 days, and

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[31] 600 Ksh was chosen as the initial cost for the improved quality LED rechargeable flashlight because some study participants consider it an affordable price and because it was a price viewed as appropriate by a manufacturer working on designing an improved flashlight for the African lighting market.

[32] The increased cost of the improved capacity LED dry cell flashlight reflects a more durable housing that will have a long lifespan, assumed to be one year, six times longer than the regular LED dry cell flashlight.

[33] The median reported lifespan of two months was used rather than the average mean reported lifespan of 3.5 months (see page 64 footnote 23 for an explanation).

[34] The improved capacity batteries have 2.5 times the capacity as the *regular* dry cell batteries and are twice the cost (this capacity/cost ratio is based off batteries currently available in Kenya). Having 2.5 times the capacity, I have then assumed the battery will last 2.5 times as long, therefore needing to be replaced less often.

[35] Under high-use situations (e.g. with the night watchmen), no data indicating the lifespan of dry cell batteries in incandescent flashlights was reported. Therefore the same ratio reported by households for time between replacing batteries in LED flashlight vs. and incandescent flashlight was used, approximately 1:2.

2. *Regular* dry cell batteries are replaced every 14 days in incandescent flashlights and every 30 days in LED flashlights, and *improved* capacity dry cell batteries are replaced every 75 days.[34]

For two reasons, no one-year cost analysis has been included for the incandescent rechargeable flashlight. First, incandescent rechargeable flashlights are not commonly available within the market (as indicated by the lack of representation of these flashlights in the Johnstone et al. 2009 study). Secondly, the one incandescent rechargeable light reported in this study initially used LEDs, but when the LEDs no longer functioned the owner replaced them with an incandescent bulb. As for the *improved* quality flashlight cost estimates, I have chosen to only include flashlights using LED technology, as it has greater potential advantages over incandescent bulbs.

Table 7 One-year cost of ownership for high intensity users of the three different types of flashlights, plus an estimated annual cost for two types of improved flashlights. One analysis shows the cost if the owner must pay 20 Ksh (Kenya Shillings) to charge their rechargeable flashlight, while the other is for the case where they can charge for free.

	High Intensity Annual Cost of Ownership	
Flashlight Type	Charging fee - 20 Ksh	No charging fee
LED Rechargeable	Ksh 3,333 ($43.86)	Ksh 900 ($11.84)
LED Dry Cell	Ksh 15,200 ($200.00)	
Incandescent Dry Cell	Ksh 29,500 ($388.16)	
Improved Quality Flashlights		
Improved Quality LED Rechargeable	Ksh 3,033 ($39.91)	Ksh 600 ($7.89)
Improved Capacity LED Dry Cell	Ksh 11,980 ($157.63)	

Table 8 One-year cost of ownership for low intensity users of the three different types of flashlights, plus an estimated annual cost for two types of improved flashlights. One analysis shows the cost if the owner must pay 20 Ksh (Kenyan Shillings) to charge their rechargeable flashlight, while the other is for the case where they can charge for free.

	Low Intensity Annual Cost of Ownership	
Flashlight Type	Charging fee - 20 Ksh	No charging fee
LED Rechargeable	Ksh 1,943 ($25.56)	Ksh 900 ($11.84)
LED Dry Cell	Ksh 1,330 ($17.50)	
Incandescent Dry Cell	Ksh 1,864 ($24.53)	
Improved Quality Flashlights		
Improved Quality LED Rechargeable	Ksh 1,643 ($21.62)	Ksh 600 ($7.89)
Improved Capacity LED Dry Cell	Ksh 884 ($11.63)	

For high-intensity flashlight users, the one-year cost of ownership for a dry cell powered flashlight is significantly greater than the cost of owning a rechargeable flashlight. For those who own rechargeable flashlights, recharging for free saves roughly 70 to 80% of the costs over a year period as compared to paying a recharging fee. Under the high-intensity use assumptions, the incandescent dry cell flashlight has a much higher cost than the LED dry cell flashlight (48% more costly). If improved quality flashlights were to be made available in accordance to the assumptions stated, the cost of the *improved* quality LED rechargeable flashlight would save high-intensity *regular* LED rechargeable flashlight owners roughly 10% to 33% annually. The cost of the *improved* capacity LED dry cell flashlight would save high-intensity *regular* dry cell flashlight owners roughly 20% to 60% annually. Examining month-to-month costs for high intensity flashlight users, after about nine months the *improved* LED rechargeable flashlights begin to see a cost-savings over *regular* LED rechargeable flashlights, while in less than two months the *improved* capacity LED dry cell flashlight sees a costs-savings over the *regular* LED dry cell (Figure 28).

For low-intensity flashlight users, over a one-year period the cost of owning a LED rechargeable flashlight is 46% higher than owning a dry cell LED flashlight if the user must pay a charging fee for the rechargeable flashlight. LED rechargeable flashlights and the dry cell incandescent flashlights, however, have roughly the same ownership cost if the user pays a charging fee. If no fee is paid then the LED rechargeable is about half the cost of the incandescent dry cell flashlight. If improved quality flashlights were to be made available, again in accordance with the assumptions stated, the cost of the *improved* quality LED rechargeable flashlight would save low-intensity *regular* LED rechargeable flashlight owners roughly 15% to 33% annually. The cost of the *improved* capacity LED dry cell flashlight would save low-intensity *regular* dry cell flashlight owners roughly 34% to 57% annually. Examining month-to-month costs for low intensity flashlight users, after about nine months the *improved* LED rechargeable flashlights begin to see a cost-savings over *regular* LED rechargeable flashlights. After only about four months the *improved* capacity LED dry cell flashlight sees a costs-savings over the *regular* LED dry cell and a cost-savings after two and a half months compared to the LED dry cell (Figure 29).

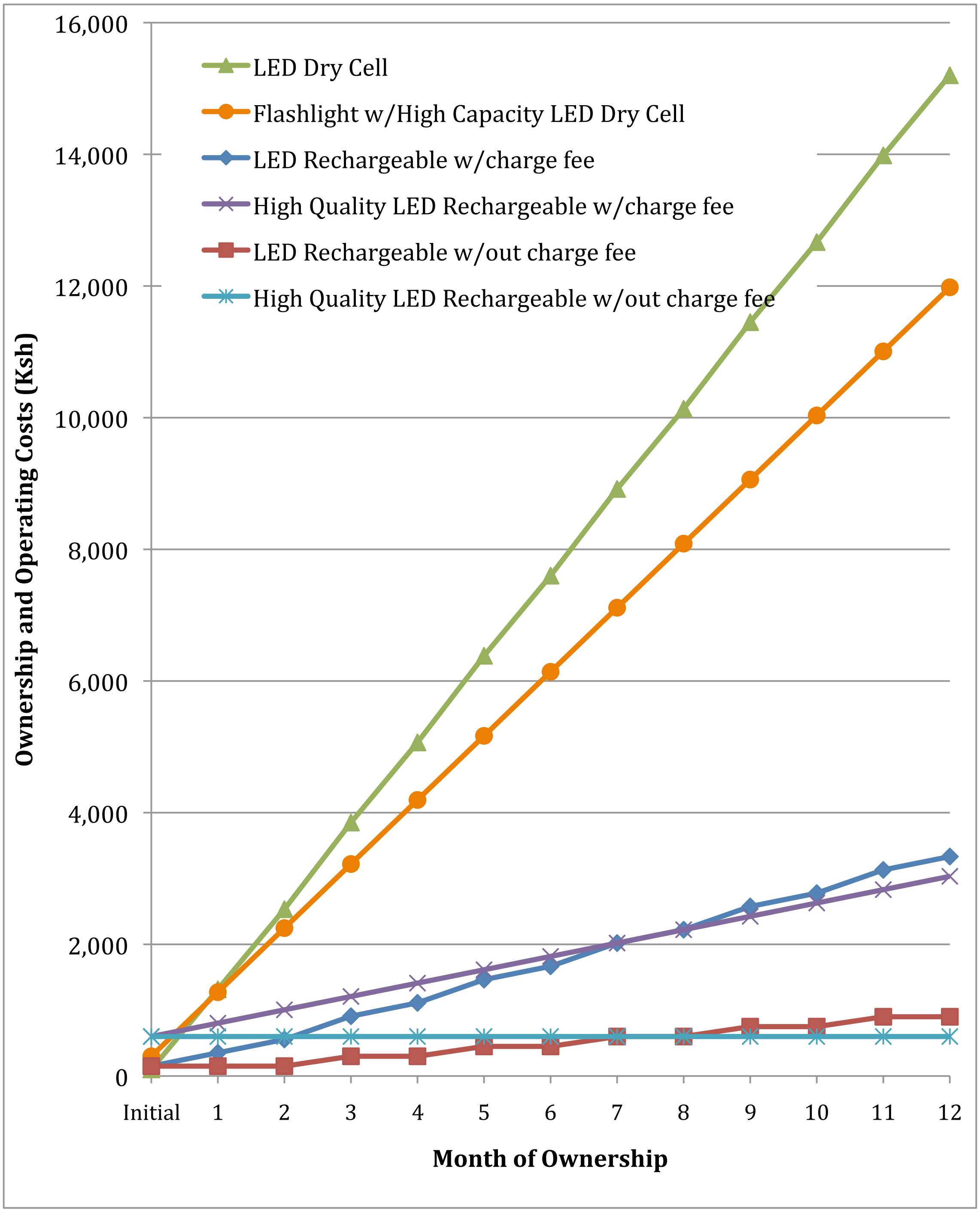

Figure 28 Month-to-month costs to own and operate the *regular* flashlights and the *improved* flashlights for high intensity flashlight users. The cost line crosses the y-axis at the initial purchase cost of the flashlight.

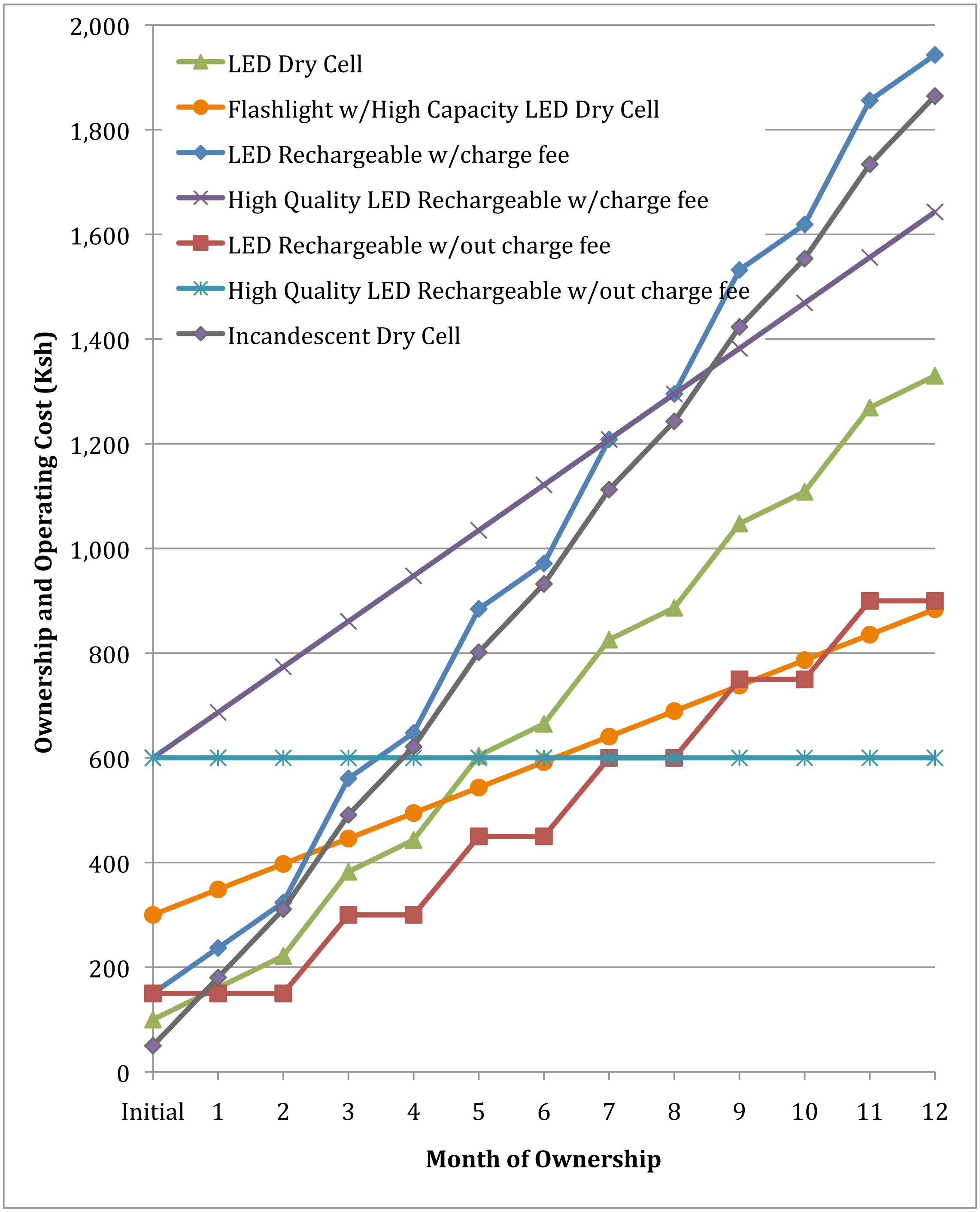

Figure 29 Month-to-month costs to own and operate the *regular* flashlights and the *improved* flashlights for low intensity flashlight users. The cost line crosses the y-axis at the initial purchase cost of the flashlight.

In the low-intensity use cases where the annual cost to operate a rechargeable flashlight (blue diamond line in Figure 29) is higher than the dry cell flashlights (purple x and green triangle lines in Figure 29), this is due to a combination of factors. First, there is a higher initial cost to purchase the flashlight. Second, is the necessity of paying the charging fee, which, as reported by low-intensity flashlight users, is about a 30% greater monthly cost than to replace dry cell batteries.

In general, of the participants owning a rechargeable flashlight, those who are able to recharge for free either at their home or at their workplace pay roughly half as much over a one year period. High-intensity flashlight users are better off owning a rechargeable flashlight versus a dry cell powered flashlight to save on cost. For low-intensity flashlight users, the cost difference between the various scenarios is small except in cases where rechargeable flashlights can be charged for free. Taking into consideration the improved quality flashlights, it is obvious that flashlight users under all use patterns and under all flashlight types would save a substantial amount of money each year if such improved products were made available even though the initial cost would be three to four times higher.

Taking average monthly earnings into account, I have estimated the percentage of annual income that flashlight ownership consumes. The outcome is dependent upon the flashlight type and the amount paid to charge. The analysis follows the assumptions made for the high-intensity use pattern in the case of night watchmen and bicycle taxi drivers and assumptions for the low-intensity use pattern for households. Overall, night watchmen spent more of their annual income on flashlights than either of the other two groups, with bicycle taxi drivers spending the smallest fraction of their annual income. Households used between 1.5 to 3.2% of their annual income, bicycle taxi drivers used between 0.8 to 2.8%, and the night watchmen used between 2.0 to 7.4% typically. However, if night watchmen were to use dry cell powered LED flashlights regularly, they would use one-third of their annual income on owning and operating a flashlight. This may explain why they do not use this type of flashlight (Table 9).

Table 9 Percentages of annual income spent on owning and operating flashlights over one-year by group and the cost to charge. The blackened cells indicate that the group did not use that type of flashlight, so no assessment was possible.

	% of Annual Income		
	w/ charging fee of 20 Ksh		
	LED Rechargeable	LED Dry Cell	Incandescent Dry Cell
Night watchmen	7.4%	33.8%	
Bicycle taxi drivers	2.8%		
Households	3.2%	2.2%	3.1%
	w/out charging fee		
	LED Rechargeable	LED Dry Cell	Incandescent Dry Cell
Night watchmen	2.0%	33.8%	
Bicycle taxi drivers	0.8%		
Households	1.5%	2.2%	3.1%

If the improved quality flashlights were available, night watchmen could reduce the percentage of annual income spent on flashlights from between 2.0% and 33.8% to between 1.3% to 22.3%, bicycle taxi drivers from between 0.8% and 2.8% to between 0.5% and 2.6%, and households from between 1.5% and 3.2% to 1.0% and 2.7%. Though all groups would end up spending less of their annual income on owning and operating an *improved* flashlight, it is clear that the night watchmen might likely be the group that would see the greatest financial savings. Furthermore, savings would be even greater if the initial cost estimated for the *improved* flashlights were less than the assumed 600 Ksh (rechargeable LED) and 300 Ksh (dry cell LED), or if the cost of improved capacity dry cell batteries were less than the assumed cost. Because the assumptions made under the *improved* flashlight estimates were hypothetical and based on loosely defined parameters, the cost estimates stated are open to interpretation.

User Preferences for an Improved Flashlight

When prompted to describe what features a good quality flashlight should have, the survey participants mentioned 20 different attributes (Figure 30). The most commonly cited feature was a battery with a larger capacity, so that it could be replaced or recharged on a less frequent basis. This is a logical request given the inconvenience and cost of charging batteries, combined with the fact that charging fees vary little if at all as a function of battery size across the range of batteries commonly used in flashlights. Four other frequently mentioned categories comprised another 45% of the preferred features: (i) a more durable housing that does not break when dropped, (ii) a sharper (more focused) beam, (iii) a more durable switch that does not break and from which the wires do not disconnect, and (iv) higher levels of light output (i.e. "Brighter"). The eleven features that were only mentioned by two or fewer participants were categorized on the graph as "Other." This group consists of the following features: a longer flashlight lifespan, a light that emits a warm color, a better charging mechanism on the rechargeable flashlights, an alarm, a better battery mounting platform that prevents the battery from shifting within the flashlight, better wire connections that do not become disjointed, an integrated holder so it is easier to mount the flashlight on a bicycle, a bubble level, LEDs in multiple locations (not just on one side), blinking light option, and rust prevention.

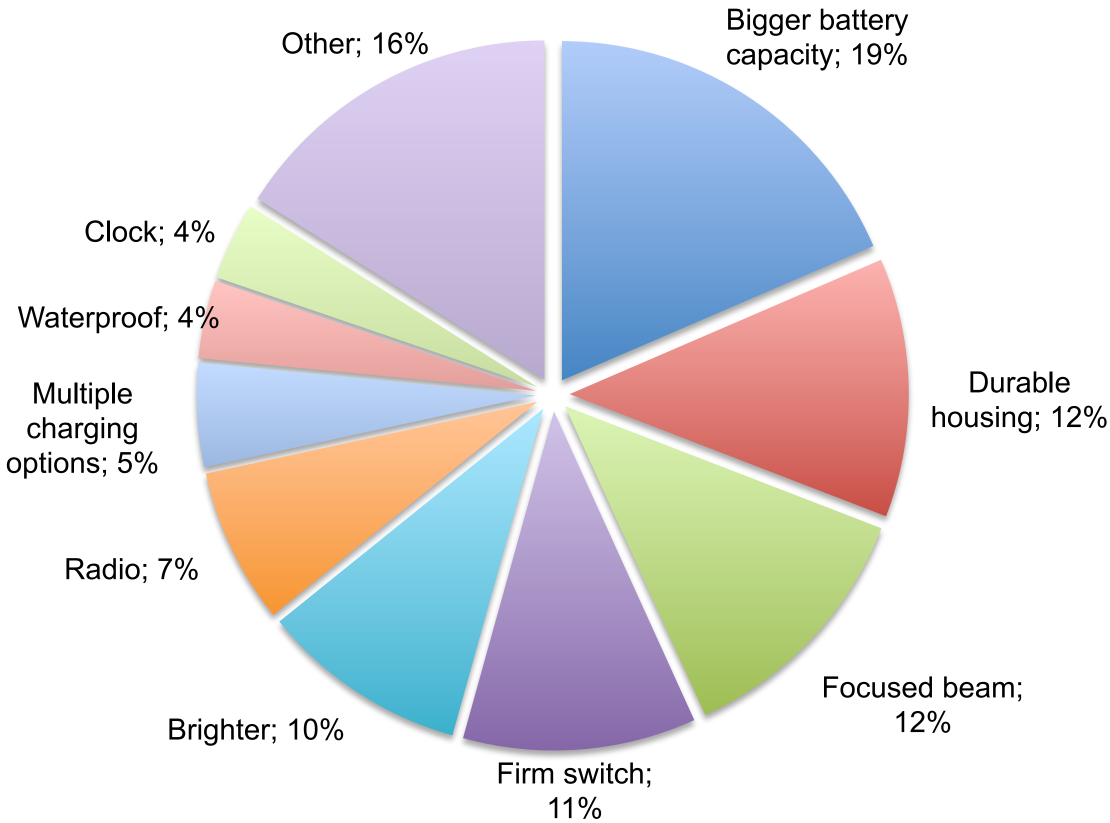

Figure 30 Summary of attributes the 46 survey respondents felt were the most important in a quality flashlight. Five dominant categories made up 64% of the preferred features: bigger battery capacity, durable housing that does not break when dropped, focused beam, durable/firm switch that does not break easily, and brighter.

Health & Environmental Implications

Based on the 41 reported survey responses from the flashlight end users in my study, both rechargeable and dry cell flashlights last for a median period of about two months before malfunctioning and requiring replacement (89%). Survey respondents of dry cell powered flashlights further reported a median of 14 days between replacing dry cell batteries in their non-rechargeable flashlights.[36] As is commonly the case throughout Kenya, rechargeable flashlights owned by the study participants use sealed lead-acid (SLA) 4-volt batteries, and dry cell powered flashlights use zinc-carbon disposable D cell batteries. Furthermore, of the 17 participants owning dry cell flashlights, 80% require two batteries and the remaining 20% only require one battery. The typical size of both a rechargeable SLA battery and a D cell battery are approximately equivalent, measuring 52 cm^3.[37] The typical volume of commonly available rechargeable and non-rechargeable flashlights is 237 cm^3.[38] Additionally, the typical weight of a 4-volt SLA battery used in rechargeable flashlights is 175 grams, of which 105 grams are due to lead. These values will be used in the forthcoming estimates of waste accumulation and lead exposure.

Rechargeable flashlights have both environmental and health advantages and disadvantages relative to dry cell powered flashlights. In comparison, over the life cycle

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[36] The median values for reported flashlight lifespan and days between replacing dry cell batteries were used to estimate the amount of waste accumulation and lead disposal rather than the average of all reported values (refer to page 64, footnote 23 for an explanation).
[37] The size of the rechargeable SLA battery is not pertinent to my solid waste accumulation estimates because I assume that the rechargeable batteries remain in the flashlight at the time of disposal: this is true because rechargeable batteries are not typically replaced.
[38] This assumption is based on the size of the most widely used flashlights identified in this study and also assumes the flashlight housing is not crushed upon being discarded.

of the product,[39] rechargeable flashlights produce a lower volume of accumulated waste since their batteries are never replaced. Over the typical two-month lifespan of a flashlight, non-rechargeable flashlights will produce more than six times the volume of waste than a rechargeable flashlight would produce, due to battery replacements. Regarding toxicity, however, as mentioned previously, the rechargeable flashlights are more problematic. The lead in the rechargeable SLA batteries is highly toxic while the zinc-carbon in dry cell batteries is relatively benign (Batteries and the Environment 2001). Since Kenya has no system for small battery disposal or the recycling of other flashlight components, non-working flashlights and batteries are often strewn on the ground or tossed in latrines (Figure 31). In the case of SLA batteries these disposal habits pose a risk of lead contamination of soil and water.

Figure 31 Common Eveready™ D cell batteries disposed of on the ground outside a household in Maai Mahiu. The left photo shows the battery crushed and open exposing the inside components of the battery.

[39] The life cycle of a product refers to the typical length of time from production to disposal.

Compiling results from my use pattern data and data on the demographics in Kenya, I have estimated the annual magnitude of lead disposal and waste accumulation from flashlight use in Kenya. As stated earlier, in a 2002 survey conducted throughout Kenya over half of the respondent households reported owning a flashlight. The population in Kenya is approximately 39 million (CIA 2009) with an average household size of 5 people (Kieyah and Nyaga 2008). So, if 3.9 million households owned a flashlight that needed to be replaced every two months,[40] then in a one-year period over 23 million flashlights would be discarded. Furthermore, assuming that 60% of those flashlights were powered by disposable dry cell batteries and 40% by rechargeable batteries,[41] and that 80% of the non-rechargeable flashlights used two batteries and 20% used one battery,[42] then 9.4 million SLA batteries and over 650 million dry cell batteries would be discarded (see Appendix F for waste accumulations equations used to derive the estimates). Estimates based on these parameters, however, may not accurately describe the situation in all of Kenya. Since the estimates for flashlight use and disposal patterns were gathered from rural populations that have limited access to electricity, it could be argued that although half of all Kenyan households may own flashlights, only the rural households with limited electricity access use flashlights as described by my data. In this case it may be appropriate to make an adjustment and to re-calculate using the initial population of 29.4 million, the number of people who lack access to electricity in Kenya. Under this scenario, annually 17.6 million flashlights, 7.1 million SLA

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[40] As documented by my study.
[41] Percentages calculated in a preliminary baseline study (Johnstone et al. 2009).
[42] As documented by my study.

batteries and 495 million dry cell batteries are disposed of (see Appendix F for waste accumulation equations used to derive the estimates).

Based on these parameters, the total amount of lead disposed of annually in Kenya as a result of flashlight use amounts to somewhere around 740,000 kilograms to nearly one million kilograms, depending upon initial population size (Table 10) (see Appendix G for equations used to derive the estimates). As far as solid waste goes, between 12 and 16 Olympic-sized pools would be filled each year; producing between 30,000 m^3 and 40,000 m^3 of solid waste annually (Table 10) (see Appendix F for waste accumulation equations used to derive the estimates). If flashlight quality were improved and flashlights lasted for one year versus the reported typical two months, on an annual basis lead disposal from flashlight use would decrease to between 123,000 kilograms to 164,000 kilograms and solid waste accumulation would be reduced to between 5,000 m^3 and 6,600 m^3. The health and environmental consequences of flashlight use can therefore be substantially decreased if flashlights were made to last longer.

Table 10. Estimate of the annual quantity of lead entering the waste stream and total annual waste accumulation from flashlight use in Kenya.[43]

	All of Kenya	**Rural Kenya**
PARAMETERS		
Population Size	39,000,000	29,400,000
Average Household Size	5	
% Households owning flashlights	50%	
Prevalence rate of rechargeable LED flashlights	40%	
Yearly household flashlight consumption	6	
Estimated weight of a 4V SLA battery[44] (g)	175	
Lead content of SLA battery (Linden 2002)	60%	
RESULTS		
Total SLA batteries discarded per year	9,360,000	7,060,000
Mass of batteries discarded per year (kg)	1,640,000	1,240,000
Total lead discarded per year (kg)	983,000	741,000
Total lead discarded per year if flashlight quality improved and products lasted 1 year (kg)	177,000	130,000
PARAMETERS		
Rechargeable LED flashlight market share	40%	
Dry cell flashlight market share	60%	
% of dry cell flashlights using 2 batteries	80%	
% of dry cell flashlights using 1 battery	20%	
Days between replacing dry cell batteries	14	
Volume of dry cell D batteries (cm^3)	52	
Volume of flashlight housing (cm^3)	237	
RESULTS		
Total number of flashlights discarded per year	23,400,000	17,600,000
Total dry cell batteries disposed of per year	659,000,000	497,000,000
Total annual waste accumulation (m^3)	39,800	30,000
Total annual waste accumulation if flashlight quality improved and products lasted 1 year (m^3)	6,600	5,000

[43] See Appendix G for the equations used in estimating the quantity of lead entering the waste stream.
[44] Weight assessed using a My Weight Balance 5500 and a single 4-volt SLA battery removed from a flashlight purchased in Kenya.

The short lifespan of these low-quality flashlights and the use of SLA batteries present health and environmental impact concerns by way of excessive waste accumulation and lead contamination. If the environmental impacts inherent to low-quality flashlights use in Kenya are to be addressed, the current system needs a change. Two modifications to the current system present themselves as potential methods for action addressing the health and environmental impact concerns raised here.

First, higher quality, low-cost flashlight products need to be made available to flashlight end users. Flashlights that last longer than a few months can have substantial affects on reducing waste accumulation. Furthermore, improving quality by using a rechargeable battery type other than SLA, such as Nickel Metal Hydride (NiMH) or Lithium-ion, can also reduce the health and environmental implications of flashlights. The disposable zinc-carbon dry cell batteries already used widely throughout Kenya have a minimal toxicity concern, but they do pose a sizeable waste accumulation concern. Making affordable high ampere-hour capacity batteries available to low-income flashlight users could be a potential solution resulting in less battery waste.

A second approach that will lend itself to reducing the health and environmental implications is to have a proper battery disposal system and the capacity to reuse and recycle flashlight batteries and other components. Improving the waste management system within Kenya, through proper battery disposal and the recycling of batteries and other flashlight components, may be the more complex option to implement. Offering some sort of an incentive for people to dispose of their dead batteries at a central collection facility so that they can later be recycled may limit the negative health and environmental impacts of inappropriate battery disposal. Such an incentive strategy has proved effective in many circumstances where changing peoples' behavior is in order (Lankey and McMichael 1999, Ostrum 2007). A potentially promising option might be piggybacking on the car lead acid battery recycling facilities currently operating in Kenyan, including a recycling operation run by a battery industry leader Associated Battery Manufacturer (ABM). Piggybacking on a pre-existing lead acid recycling program might be a cost-effective option for recycling SLA flashlight batteries and would be worth further exploration.

CONCLUSION & RECOMMENDATIONS

The overarching message revealed through both the lab-based performance testing and field evaluations is that of alarming concern regarding flashlights in Kenya. The invaluable role of a flashlight in the lives of my participants, Kenyans as a whole, and people living in developing countries throughout the world, paired with such poor quality flashlight products, results in a number of significant social, economic, health and environmental repercussions.

The results of the performance testing indicated considerable variation within and between models, and also confirmed that the performance of the flashlights fell below the manufacturers' specifications for the two metrics for which advertised values were available. These results raise concerns about the performance of these flashlights, and they indicate that the respective manufacturers should re-evaluate their product ratings to match actual performance. It is important to note that these test results, while valuable, do not provide information about key measures of product quality and durability, such as lumen depreciation over time, battery life, vulnerability to breakage, and quality of the wiring, switches, and solder joints. Such measurements would provide additional important information about the performance of these flashlights. Moreover, the test results presented here represent the performance of only three of the many models of flashlights that are available. A more comprehensive study covering a wider range of products would be very valuable.

An understanding of the most common complaints of flashlight users in Kenya and their input concerning the preferred features of a quality flashlight product are essential for manufacturers wishing to improve their products as well as to those who are working to develop policies and institutions aimed at ensuring the success of the off-grid lighting market through the availability of quality products. This study has identified LED failure, water leakage leading to corrosion and electronic component failure, battery failure to maintain a charge, and switch failure as the most common complaints reported by a small sample of flashlight users in Kenya. A more in depth field analysis of flashlight user complaints paired with communication of the results to manufacturers could be the necessary first steps toward ensuring a stable and sustainable flashlight market.

Furthermore, understanding use patterns and estimating the cost of owning and operating the low-cost flashlights that are currently available in the off-grid lighting market is essential to address quality assurance concerns. An understanding of the annual costs to which flashlight users are subject can assist decision makers to identify improved quality flashlights of slightly higher cost that would still be affordable to users on an annual basis. While higher quality flashlights may have a higher initial cost, they are likely to have a comparable, if not lower, overall annual cost of ownership. Under use patterns reported by participants in this study flashlight users may spend as little as 900 Ksh ($12) to as much as 30,000 Ksh ($400) annually in ownership and operating costs. This can be as much as 33% of an individual's annual income. Kenyan flashlight owners have expressed serious dissatisfaction with the flashlights that are currently available to them, and some have indicated a strong interest in purchasing higher quality flashlights provided that the associated cost increase is modest. With this in mind, a company that could deliver a rugged, good quality, moderately priced (i.e., $7-10; 550-750 KSh) rechargeable LED flashlight to the Kenyan market could be in a position to deliver superior portable lighting services to low income Kenyans. Demand for such products may be especially strong among high intensity users such as the night watchmen and bicycle taxi drivers interviewed in this study. Improved quality flashlights may offer savings up to 68% when compared to options currently available. However, the delivery of such a flashlight would need to be accompanied by a successful marketing campaign aimed at differentiating the product from the very low quality products that are currently available in the market. A market trial study where higher quality moderately priced flashlights are made available for purchase to low income flashlight users would provide further information that could greatly increase the success of marketing improved quality flashlights.

Also as shown by this study are the alarming implications that flashlights in Kenya have upon people's health and the environment. Improving the quality of flashlights on the market, along with addressing waste management streams may reduce these potentially dangerous implications. Annually, the amount of lead disposed of and the volume of solid waste accumulation could potentially both be reduced by more than 80%. Health risk can be limited if flashlights are made with low or non-toxic components. A switch from using sealed lead-acid batteries (SLA) to either nickel-metal hydride (NiMH) or lithium-ion batteries would decrease the health risks of rechargeable flashlight batteries. Meanwhile, increasing the lifespan of a flashlight beyond a couple of months and making available affordable, higher capacity dry cell batteries can reduce waste accumulation. Furthermore, recycling flashlight plastic housings and batteries could lessen environmental impacts by reducing waste accumulation and diminish health risks by properly disposing of the lead in SLA batteries. My assessment of the health and environmental impacts of flashlight use in Kenya raises awareness, but is preliminary at best. Further studies addressing these concerns at greater depth would offer more certainty to many of my assumptions and estimation, providing greater clout where policy changes are warranted.

This study reveals serious quality problems with LED flashlights, which are the LED products that have achieved the greatest levels of market penetration in developing countries. It highlights the need for a quality assurance program that helps to protect the interests of low-income end users such as the flashlight users that participated in this study.

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APPENDIX A. CCT X,Y CONVERSION EQUATION

$$CCT = A_0 + A_1 \exp(-n/t_1) + A_2 \exp(-n/t_2) + A_3 \exp(-n/t_3)$$

$$n = (x - x_e) / (y - y_e)$$

	Valid CCT Range (K)	
Constant	3000-50,000	50,000-8 x 10^5
x_e	0.3366	0.3356
y_e	0.1735	0.1691
A_0	-949.86315	36284.48953
A_1	6253.80338	0.00228
t_1	0.92159	0.07861
A_2	28.70599	5.4535 x 10^{-36}
t_2	0.20039	0.01543
A_3	0.00004	
t_3	0.07125	

APPENDIX B. PHOTO GALLERY

Photo 1 The group of Night Watchmen study participants.

Photo 2 Bicycle Taxi Driver transporting clients. The center bicycle has an orange flashlight mounted on the handlebars.

Photo 3 Bicycle Taxis with flashlights mounted on the handlebars.

Photo 4 One of the households participating in the flashlight survey.

Photo 5 Household study participant holding a LED dry cell flashlight.

Photo 6 Yage 3166 flashlight used for datalogger integration and distributed to the night watchmen.

Photo 7 Yage 3166 flashlight with integrated datalogger distributed to the night watchmen.

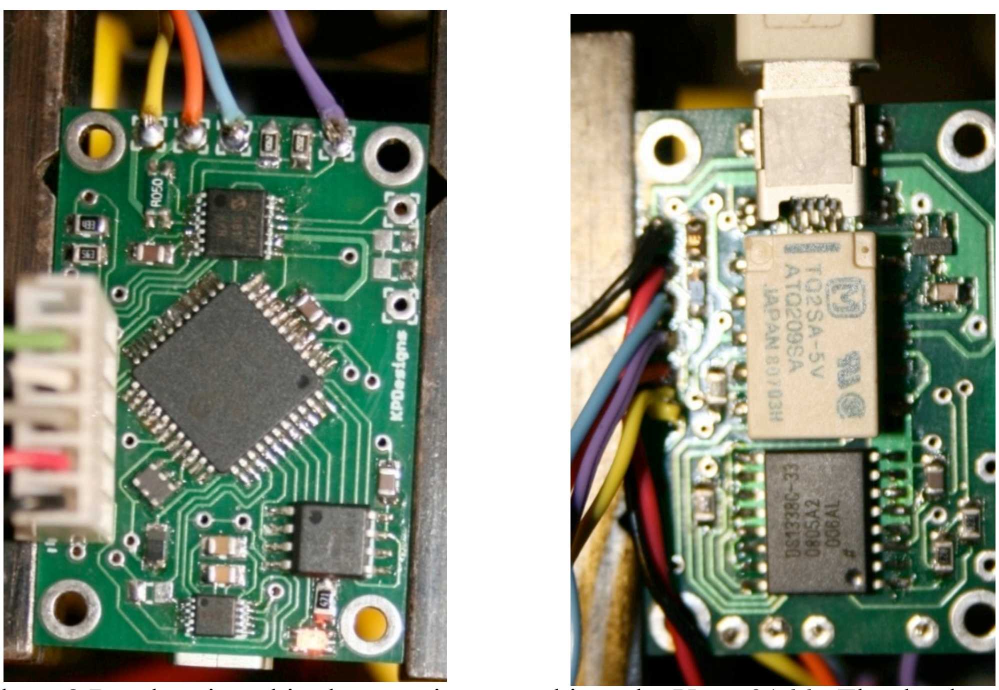

Photo 8 Datalogging chip that was integrated into the Yage 3166. The datalogger records the time stamp, current and voltage. A mini-USB connection allows for the data to be downloaded (right side).

Photo 9 Corrosion from water and battery leakage.

Photo 10 A household flashlight that had a failed switch and was rewired by the user.

Photo 11 Broken Yage 3166 datalogger torch after being dropped and fixed multiple times.

Photo 12 Side view of broken charge plug on the Yage 3166 flashlight.

Photo 13 LED flashlights, used by a household, that require two dry cell D batteries.

Photo 14 LED flashlights used by a household that require only one dry cell D battery.

APPENDIX C. SURVEY FORMS

Night Watchmen Survey

Survey Form
Portable Lamps in Kenya
June, 2009

Askari SURVEY

Survey by: Jenny Tracy
Humboldt State University
Arcata, CA 95521, USA

Section 1: General Information (filled in prior to starting interview):

1.1 Name of person(s) administering survey: ______________________________

1.2 Date & time of interview: ____

1.3 Town: _____________________

1.4 Participant ID # _______ **1.5 Torch ID # _________**

##

1.6 What is the **name** of the person being interviewed?

Name: ____

1.7 **Gender:** Female (1) Male (2)

1.8 Who do you work for? **Employer**:
____

1.9 Where in town are you stationed? **Location**:
____

1.10How long have you **worked** as an Askari?

1.11 Note their monthly income: ____________________

<u>Section 2: Torch Use</u>

2.1 What **model** of torch do you **currently** use? (Describe the torch if no name, i.e. number of LEDs, rechargeable/dry cell, number of light settings).

2.1.1 How long ago did you **start using** the torch you use now? # **Months ________**

2.2 What **model** of torch did you use **previous** to the one you currently use? (Describe the torch if cannot remember the name, i.e. number of LEDs, rechargeable/dry cell, number of light settings).

2.2.1 How long did that torch **last**? # **Months _______**

2.2.2 Why did you **replace** it?

2.3 In the last 6 months, how many torches have you **used**?# **_______**

2.3.1 In **your opinion**, of the torches you have used in the past, which one was the **best**? **Why** was it better?

Best torch: ____

Why better: ____

2.4 How do you **get** your torches?

I buy (1) Employer gives (2) Other ____________________ (3)

2.5 How much do the torches **initially cost**? **Cost: _________**

2.6 If the torch is rechargeable, how do you **charge** it AND how often do you charge? If it uses dry cell batteries, what type of batteries AND how often do you **replace** them?

Rechargeable (1) Charging Method: ______________________________

How often recharge: _____________________________

Dry Cell (2) Model Name: ___________________________________

How often replace: ______________________________

2.6.1 **Who pays** for the charge/batteries?

2.6.2 What is the **cost** to charge or to buy replacement batteries? **Cost: ________**

2.7 Approximately how many **hours per night** is the torch turned on? **# Hours: _____**

<u>Section 3: What would be an ideal torch?</u>

3.1 How much would you **pay** for a better quality torch that lasted for at least 2 years?

More than1000 [1] 800-1000 [2] 600-800 [3]

400-600 [4] 200-400 [5] Less than 200 [6]

3.2 Would you prefer a **rechargeable** torch or one that used **dry cell** batteries?

Rechargeable [1] Dry Cell Batteries [2]

3.2.1 If you prefer rechargeable, would you prefer to **charge** a torch by

Grid [1] Solar [2] Both Grid & Solar [3] Crank [4]

3.2.2 How **often** would you be able and willing to **charge** the torch?

Everyday [1] Every 2 days [2] Every 4 days [3]

Once per week [4] Once every two weeks [5]

3.2.3 What factors may **limit** you from charging?

Security of Solar [1] Access to the Grid [2] Grid Charge Cost [3]

Other Limiting Factors: ____

3.3 What **features** would you like the torch to have?

Bicycle Taxi Driver Survey

Survey Form
Portable Lamps in Kenya
June, 2009

Torch Use: Boda Boda SURVEY

Survey by: Jenny Tracy
Humboldt State University
Arcata, CA 95521, USJA

Section 1: General Information (filled in prior to starting interview):

1.1 Name of person(s) administering survey: ______________________________

1.2 Date & time of interview: ____

1.3 Town: _____________________ **1.4 GPS point ______________**

1.5 Participant ID # _______

##

1.12What is the **name** of the person being interviewed?

Name: ____

1.13**Gender:** Female (1) Male (2)

1.14Who do you work for? **Employer**:

____

1.15Where in town are you stationed? **Location**:

____

1.16How long have you **worked** as a Boda Boda driver?

1.17 Note their monthly income: ____________________

Section 2: Torch Use

2.8 What **model** of torch do you **currently** use? (Describe the torch if no name, i.e. number of LEDs, rechargeable/dry cell, number of light settings).

2.8.1 How long ago did you **start using** the torch you use now? # **Months ________**

2.9 What **model** of torch did you use **previous** to the one you currently use? (Describe the torch if cannot remember the name, i.e. number of LEDs, rechargeable/dry cell, number of light settings).

2.9.1 How long did that torch **last**? # **Months _______**

2.9.2 Why did you **replace** it?

2.10In the last 6 months, how many torches have you **used**?# **_______**

2.10.1 In **your opinion**, of the torches you have used in the past, which one was the **best**? **Why** was it better?

Best torch: ____

Why better: ____

2.11How do you **get** your torches?

I buy (1) Employer gives (2) Other ____________________ (3)

2.12How much did you current torch **initially cost**? **Cost: _________**

2.13If the torch is rechargeable, how do you **charge** it AND how often do you charge? If it uses dry cell batteries, what type of batteries AND how often do you **replace** them?

Rechargeable (1) Charging Method: _______________________________

How often recharge: ______________________________

Dry Cell (2) Model Name: ___________________________________

How often replace: _____________________________

2.13.1 **Who pays** for the charge/batteries?

2.13.2 What is the **cost** to charge or to buy replacement batteries? **Cost: ________**

2.14Approximately how many **hours per night** is the torch turned on? **# Hours: ____**

Section 3: What would be an ideal torch?

3.1 How much would you **pay** for a better quality torch that lasted for at least 2 years?

More than1000 [1] 800-1000 [2] 600-800 [3]

400-600 [4] 200-400 [5] Less than 200 [6]

3.2 Would you prefer a **rechargeable** torch or one that used **dry cell** batteries?

Rechargeable [1] Dry Cell Batteries [2]

4.2.1 If you prefer rechargeable, would you prefer to **charge** a torch by

Grid [1] Solar [2] Both Grid & Solar [3] Crank/Dynamo [4]

4.2.2 How **often** would you be able and willing to **charge** the torch?

Everyday [1] Every 2 days [2] Every 4 days [3]

Once per week [4] Once every two weeks [5]

4.2.3 What factors may **limit** you from charging?

Security of Solar [1] Access to the Grid [2]

Grid Charge Cost [3] **Other Limiting Factors**:_________________________

3.3 What **features** would you like the torch to have?

Household Survey

Survey Form
Portable Lamps in Kenya
June, 2009

Torch Use: Household SURVEY

Survey by: Jenny Tracy
Humboldt State University
Arcata, CA 95521, USA

Section 1: General Information (filled in prior to starting interview):

1.1 Name of person(s) administering survey: ______________________________

1.2 Date & time of interview: ______________________________

1.3 Town: ____________________ **1.4 GPS point**: __________

1.5 **Household ID # __________**

1.6 What is the **name** of the person being interviewed?

Name: ____

1.7 **Gender:** ☐ Female [1] ☐ Male [2]

Section 2: Demographic Information

2.1 What are the major sources of income for your household (check all that apply and indicate the greatest source with a **#1**)?

☐ Business (kiosk / shop / selling goods / etc.)>*type:* ____________________ [1]
☐ Jua Kali (mechanic / carpenter / dress making / etc.) [2]
☐ Salary / Professional work (ex: teacher) >*source*: ____________________ [3]
☐ Farming [4]
☐ Remittance [5]
☐ Other ____ [6]

2.2 How many **people** are in your household? #___________

2.3 Do you have **grid** electricity at home? ☐Yes [1] ☐ No [2]

2.4 Do you have grid electricity at your business?

☐ Yes [1] ☐ No [2] ☐ Not Applicable (does not have business) [3]

Section 3: Torch Use

3.1 In the last 6 months, how many torches have you **bought**? **# Torches: _______**

3.2 How long did the torch you used previous to your current torch last? **# Months: ___**

3.3 What are the **main problems** that you have experienced with torches?

Failure of: LEDs/Bulb [1] Battery [2] Switch [3]

Drops & breaks [4]

Other Problems experienced: ____

____

3.4 Of the torches you have used in the **past**, which one was the **best**? Why was it **better**? (Describe it if cannot remember: # of LEDs, rechargeable/dry cell, # of light settings).

Best torch: ____

Why better: ____

Section 4: What would be an ideal torch?

4.1 How much would you **pay** for a better quality torch that lasted for at least 2 years?

More than1000 [1] 800-1000 [2] 600-800 [3]

400-600 [4] 200-400 [5] Less than 200 [6]

4.2 Would you prefer a **rechargeable** torch or one that used **dry cell** batteries?

Rechargeable [1] Dry Cell Batteries [2]

4.2.1 If you prefer rechargeable, would you prefer to **charge** a torch by

Grid [1] Solar [2] Both Grid & Solar [3] Crank [4]

4.2.2 How **often** would you be able and willing to **charge** the torch?

Everyday [1] Every 2 days [2] Every 4 days [3]

Once per week [4] Once every two weeks [5]

4.2.3 What factors may **limit** you from charging?

Security of Solar [1] Access to the Grid [2] Grid Charge Cost [3]

Other Limiting Factors: ____

4.3 What **features** would you like the torch to have?

Section 3: Current Torch Use

Component	Type	Code
Bulb	LED	LED
	Incandescent	INC
Battery	Rechargeable	R
	Dry Cell (mawe)	D

Ex: LED-D

5.1 Regarding each torch you and your family currently uses

5.1.1 What **models** of torches do you own and how many of each?
5.1.2 What **type** of torch is it (use codes from table-→)?
5.1.3 How much did each torch **initially cost** you?
5.1.4 How long did the charge/batteries last before you recharged/replaced the batteries most recently?
5.1.5 How much did it **cost** you to charge/replace batteries last time?
5.1.6 How many **days ago** did the torch last get **used**?
5.1.6.1 List all the ways the torch was **used** the last time you used the torch and for how many **minutes**.

Torch #	***5.1.1***	***5.1.2***	***5.1.3***	***5.1.4***	***5.1.5***	***5.1.6***	***5.1.6.1***				
	Model	**Type**	**Initial Cost (Ksh)**	**Time Between Charge/ Replace**	**Cost Recharge /Replace (Ksh)**	**# Days Ago Last Used**	***List Ways Used and # Minutes Used for***				
1											
2											
3											
4											

APPENDIX D. PERFORMACE INDICATOR RAW DATA

Flashlight Model and Sample #	Performance Indicator						
	Battery Capacity (mAh)	Time to Attain Full Charge (hr)	Max Initial Illuminance (lux)	Run-Time (hr)	Lighting service per Charge (lux hours)	Light Distribution: Area containing 90% of total lux (m^2)	Color Rendering Index (°K)
Flashlight A1	674	16.3	312	45	2806	0.23	7.35E+24
Flashlight A2	799	17.0	302	45	2599	0.24	6.49E+09
Flashlight A3	811	16.3	321	29	2000	0.21	10895
Flashlight A4	560	16.8	353	33	1447	0.2	8851
Flashlight A5	--[45]	16.2	277	34	2360	0.23	--
Flashlight B1	337	13.0	285	25	1039	0.16	18195
Flashlight B2	433	12.2	436	17	2196	0.18	9069
Flashlight B3	431	12.6	313	23	1598	0.16	9863
Flashlight B4	469	13.1	244	15	1006	0.13	8070
Flashlight B5	370	13.0	380	22	2132	0.17	7885
Flashlight C1	798	19.8	459	20	2157	0.17	25105
Flashlight C2	756	--	--	--	--	--	--
Flashlight C3	694	20.6	522	40	3469	0.19	10290
Flashlight C4	430	19.7	587	53	3914	0.19	9466
Flashlight C5	642	19.8	495	33	3422	0.19	11808

[45] Empty cells indicate the flashlight malfunctioned before the test was performed.

APPENDIX E. DETAILED REPORT ON DATALOGGERS

Seven of the 15 night watchmen participating in the survey for my study each received a new Yage 3166 flashlight with an integrated logger and were asked to use it while working as a replacement for their current flashlight (Appendix B. Photo 6 and Photo 7). The datalogger within the flashlight recorded the time stamp, voltage, and current, providing use pattern data supplementing the use pattern data reported on the survey (Appendix B. Photo 8). The recorded data from the dataloggers were downloaded and emailed to me on a weekly basis from July until December by a research assistant in Maai Mahiu. The trial duration was approximately 150 days, but the loggers only recorded data on a fraction of those days for several reasons. First, within two weeks of the start of the trial, one of the datalogging flashlights was lost (Datalogger-5) and no data were ever received for that flashlight. Additionally, over the course of the trial, four more of the seven flashlights were lost, though two of then had stopped working before they became lost. Second, the custom dataloggers were still under development and therefore had several "bugs" that affected their logging capabilities. Third, as a result of the flashlights being poor in quality, by December four of the original seven flashlights had broken while the remaining two (excluding the one that was lost) had seriously reduced performance. Below I list all seven datalogging flashlights, Flashlight 1-7, followed by a brief description of the flashlight's lifespan.

Flashlight-1: It was lost in September, but before it was lost it had been dropped leaving the head of the flashlight broken and the flashlight no longer functioning. At the time it was lost the datalogger was still working.

Flashlight-2: The datalogger stopped working in mid-November. This is one of the two flashlights that was still working in December. In November it fell and the body of the flashlight broke, but it was mended with masking tape and still functioned properly, minus one LED. As of December the battery no longer kept a charge as it had originally and therefore needed to be recharged more frequently.

Flashlight-3: The datalogger stopped working in mid-November. This is the second of the flashlights that was still functioning in December. In October, however, it fell and the head was broken; after this the LEDs stopped working. The night watchmen then replaced the LEDs and it continued to work. As of December the battery no longer kept a charge as it had originally and therefore needed to be recharged more frequently.

Flashlight-4: The datalogger stopped working in late July. The flashlight was lost in December. Just prior to losing it, the flashlight dropped, breaking the head and leaving the LEDs non-functioning and also breaking the terminal plugs used to charge the flashlight.

Flashlight-5: The datalogger was never downloaded. The flashlight was lost two weeks into the trial.

Flashlight-6: The datalogger stopped working in mid-November. In October four of the five LEDs stopped working for no apparent reason. The LEDs were then replaced. Soon after the flashlight was dropped breaking the head, but leaving the replaced LEDs still functioning. By the end of the trial one of the LEDs appeared to work correctly, two were not working at all, and two were flickering. It was deemed no longer functional at this point (Appendix B Photo 11 and Photo 12).

Flashlight-7: The datalogger stopped working in late July. The flashlight was lost in October. Before it was lost it was dropped once, but continued to function properly. Also, before it got lost the battery kept a charge for the same amount of time that it had originally.

Overall, the datalogger trial was a success. Over the roughly 3,600-hour (150 day) trial, all seven flashlights cumulatively recorded 2,016 hours. Datalogger-1 recorded the most number of hours at 960, Datalogger-2 recorded 144 hours, Datalogger-3 recorded 360 hours, Datalogger-4 recorded 144 hours, Datalogger-5 was lost before we had a chance to download the data, Datalogger-6 recorded 384 hours and Datalogger-7 recorded only 48 hours. We also learned that the number reported by night watchmen on the survey regarding the number of hours they use the flashlight each night was substantially higher than what the dataloggers recorded, 3.5 hours versus 0.85 hours, respectively. We also were able to monitor problems the watchmen encountered with their flashlights. The primary reasons for flashlight failure appeared to be linked to dropping the light, when dropped, the flashlight head broke and the LEDs stopped functioning properly.

APPENDIX F. WASTE ACCUMULATION EQUATIONS

Equations used to estimate the volume of solid waste accumulation resulting from flashlight use

$$\frac{\text{Population}}{\textit{Average}\text{ number of people per household}} \times \text{ \% of population owning a flashlight}$$
$$= \text{ Number of households owning a flashlight}$$

$$\text{Number of households owning a flashlight} \times \frac{\text{Typical lifespan of a flashlight}}{\text{12 months}}$$
$$= \text{ Number of flashlights households discard annually}$$

$$\text{Number of flashlights households discard annually} \times \text{ \% of rechargeable LED flashlight market share}$$
$$= \text{ Number of rechargeable LED flashlights discarded annually}$$

$$\text{Number of flashlights households discard annually} \times \text{ \% of dry cell flashlight market share}$$
$$= \text{ Number of dry cell flashlights discarded annually}$$

$$\text{(Number of dry cell flashlights discarded annually)} \times \text{ (\% using 2 batteries} \times 2 +$$
$$\text{\% using 1 battery} \times 1) \times \frac{\text{365 days per year}}{\text{Number of days between replacing batteries}}$$
$$= \text{ Number of dry cell batteries discarded annually}$$

$$\text{Number of dry cell batteries discarded annually} \times \text{ Volume of a dry cell battery}$$
$$= \text{ Volume of waste produced annually from dry cell battery disposal}$$

$$\text{Number of flashlights households discard annually} \times \text{ Volume of flashlight housing}$$
$$= \text{ Volume of waste produced annually from flashlight housing disposal}$$

$$\text{Volume of waste produced annualy from dry cell battery disposal } +$$
$$\text{Volume of waste produced annually from flashlight housing disposal}$$
$$= \text{ Total volume of annual waste accumulation from flashlight use in population}$$

APPENDIX G. LEAD EXPOSURE EQUATIONS

Equations used to estimate of the quantity of lead entering the waste stream per year

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$$\frac{\text{Population}}{\text{Average household size}} = \text{Number of households in population}$$

$$\text{Number of households in population} \times \text{\% Households using flashlights}$$
$$= \text{Number of flashlight (within population)}$$

$$\text{Number of flashlights} \times \text{\% rechargeable LED flashlights in market}$$
$$= \text{Number of rechargeable LED flashlights (within population)}$$

$$\text{Number of rechargeable LED flashlights} \times \text{Annual flashlight consumption rate}$$
$$= \text{Number of rechargeable LED flashlights discarded annually}$$

$$\text{Number of rechargeable LED flashlights discarded annually} \times$$
$$\text{Average mass of 4V SLA battery} = \text{Total mass of SLA batterries discarded annually}$$

$$\text{Mass of SLA batteries discarded annually} \times \text{\% lead content of SLA batterry}$$
$$= \text{Total mass of lead potentially discarded annually}$$