High Life Cycle Efficacy Explains Fast Energy Payback for Improved Off-Grid Lighting Systems

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Supporting information is available on the *JIE* Web site

Summary

The energy intensity of fuel-based lighting is substantial given the paltry levels of lighting service, poor economic outcomes, and exposure to public health risks for users throughout the developing world. There is a great opportunity to reduce fossil energy consumption (and mitigate greenhouse gas emissions) while improving public health and economic outcomes for the poor by encouraging upgrading from fuel-based to rechargeable light-emitting diode (LED) lighting. However, switching to efficient lighting requires up-front investments of energy for manufacturing. This study explores life cycle energy performance in the market for modern off-grid lighting (OGL) products in Sub-Saharan Africa and introduces a new metric, life cycle efficacy, which facilitates comparisons and analysis of life cycle energy performance (light output per unit of embodied plus use-phase energy consumption) for lighting technology systems. Combining field insights on technology adoption dynamics with embodied energy estimates for a range of products available in 2012 shows that OGL energy "debts" are "paid back" in 20 to 50 days (substantially faster than kilowatt-scale grid-connected solar electricity systems) with energy return on investment ratios from 10 to 40. This stems from greatly improved life cycle efficacy for off-grid LED lighting (~20 lumens/watt [lm/W]), compared to fuel-based lighting (~0.04 lumens/W). Life cycle benefits—not only energy, but also economic and health benefits—depend strongly on product service lifetime (related to quality) and fuel displacement fraction (related to performance). OGL life cycle efficacy increases from longer lifetime and/or improved LED source efficacy lead to better quality and less-expensive lighting available in the developing world with lower energy use than the fuel-based incumbent technology.

Introduction

Approximately 1.3 billion people live without access to central grid quality electricity (IEA 2011) and must rely on fuel-based lighting for illumination, leading to undue economic, public health, and environmental burdens (Mills 2005; Radecsky et al. 2008; Tracy et al. 2010; Apple et al. 2010; Mills 2012). Attaining reduced greenhouse gas (GHG) emissions (from reductions in fuel consumption for lighting) is one of the key drivers for supporting modern off-grid lighting (OGL)[1] as a replacement for fuel-based lighting (Mills 2005; Dalberg Global Development Advisors 2010; Mills and Jacobson 2011). Black carbon (BC), which is a public health concern in itself, appears to be a particularly important GHG from wick-based lighting; fuel-based lighting was recently reported to account for ~7% of global BC emissions (Lam et al. 2012a). Fuel-based

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lighting health concerns include both chronic illness, such as cardiopulmonary diseases, and acute risks of fire and accidental ingestion, leading to hundreds of thousands of injuries and premature deaths annually (Lam et al. 2012b; Mills 2012). All the while, the performance of fuel-based lighting is poor (Mills 2003; Johnstone et al. 2009; Alstone et al. 2013), and people must spend significant fractions (2% to 5% or more) of their income to obtain it (Bacon et al. 2010). Fortunately, emerging alternatives—modern light-emitting diode (LED)-based OGL systems—are now rapidly being deployed through a variety of market-based and public sector programs. Currently, annual sales are at approximately 1,000,000 units and the compound annual sales growth rate is 100% to 300% (Dalberg Global Development Advisors 2013).

As the market for OGL grows, key questions remain about the impacts both globally and in households. To address one of these questions, this article presents a framework for estimating whether the energy embodied in the manufacture of modern OGL is fully recovered over its useful lifetime, a foundational analysis made important because consumption of primary energy is strongly linked to GHG emissions, economic performance, and health risks. This work combines a rigorous accounting of embodied energy for a range of contemporary OGL products with results from detailed fieldwork in rural Kenya and broader market data for sub-Saharan Africa that show the dynamics of pre- and post-adoption fuel consumption patterns. It also presents a new metric—*life cycle efficacy*—that facilitates comparing the life cycle energy performance of alternative lighting technology systems both on- and off-grid.

Approach

The life cycle performance metrics we employ for assessing OGL are energy payback and energy return on investment (EROI). The energy payback period is the amount of time it takes reductions in ongoing energy use to offset the "embodied" primary energy that was required to manufacture, transport, and install the new technology. EROI accounts for product lifetime and is a ratio of energy offsets to embodied (and operational) energy "investments."

The new metric we propose for comparing lighting technology system life cycle performance—life cycle efficacy—has units of lumens per watt on a primary energy basis (lm/$W_{primary}$). Life cycle efficacy is essentially a synthesis of light-source efficacies (e.g., 100 lm/W for a good LED circa 2013), the electricity (or liquid fuel in the case of kerosene lamps) powering the light source, and the amortized primary energy required to produce lighting products. In contrast to specifying "functional units" that define a quantity of light (usually in thousands of lumen-hours [lmhr]) and report the energy required,[2] this approach collapses the time dimension to estimate efficacy on a power basis and results in values that lend themselves to comparison among technology systems and are meaningful for understanding the component contributions to efficacy.

Patterns of fuel use before and after OGL is adopted are important inputs for life cycle performance assessments of OGL. People who adopt OGL do not universally stop using fuel-based lighting alongside, thus knowing the baseline is not enough to assess impact, which depends on the fraction of fuel that is offset. In this study, we follow a detailed field study on OGL adoption that was led by the authors as a case study for the dynamics. It showed an approximate 50% reduction in fuel use from the baseline (Alstone et al. 2013). Broader data on baseline fuel consumption and information on use patterns after adoption inform a globally relevant estimate for the impacts of modern lighting on fuel-based lighting use.

Analyses of embodied energy are well established, but only limited studies cover emerging off-grid LED lighting systems that can be used to displace fuel-based lighting in the developing world. Before 2012, no peer-review works that we know of were available on the embodied energy in improved OGL products. Two student-authored projects from 2009 reported on embodied energy of approximately tens to hundreds of megajoules (MJ) for solar lighting products with favorable energy payback, compared to the kerosene being replaced (Donohoe and Boddy 2009; Dave 2009). A more recent peer-reviewed article from 2012 uses a "traditional" life cycle assessment (LCA) framework (based on the ecoinvent database, a proprietary data source) and reports that a range of five solar lighting products (from 0.7 to 40 W solar module power, including LED and compact fluorescent lamp [CFL] sources) have significantly less environmental impact than fuel-based alternatives across a range of indicators (Durlinger et al. 2012). The article is a useful benchmark for comparing our estimates of embodied energy because it is based on a trusted—albeit closed—source of data.

We use a rigorous materials and process accounting model for embodied energy estimates that includes Monte Carlo simulations for error analysis and is based on open-source data documented in the Supporting Information on the Journal's website. The choice of open-source data facilitates the application of methods we present here beyond the scope of this study.

Research Methods

This work includes two levels of focus: a relatively narrow field-based case study and a broader market analysis. Both include estimates for the dynamics of fuel consumption impacts and embodied energy for representative OGL products.

For the field study, we compared detailed records on the amount of kerosene that was offset after adoption of LED desk lamps to the estimated embodied primary energy in each of the two lamp options—solar and grid charged—that we offered in a 2008–2009 market test in Kenya to 23 night market vendors (Radecsky et al. 2008; Johnstone et al. 2009; Alstone et al. 2013). The field study provides a case study on the dynamics of technology adoption that gives context to, and informs the structure of, the broader analysis.

The broad market analysis offers widely applicable estimates for the life cycle impact of technology adoption. Fuel-use dynamics are based on baseline kerosene consumption in sub

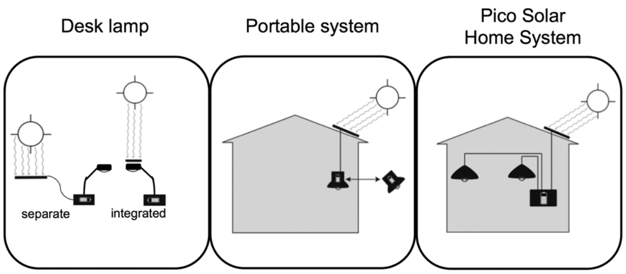

Figure 1 Off-grid lighting category types considered in this study.

-Saharan Africa from a Lighting Africa market survey of 5,000 households (Baker and Alstone 2011) and estimates of the baseline kerosene offset fraction informed by the field study and other sources. We estimated the embodied primary energy for seven OGL products that reflect the diversity of options available in 2012.

The products used in the broad market analysis can be categorized as desk lamps (n = 2), portable systems (n = 3), or pico solar home systems (PSHSs; n = 2), as shown in figure 1. *Desk lamp* products have the same appearance as conventional desk or table lamps, except they are solar charged. The solar panel is either separate (connected by a cable) or integrated into the body of the lamp. *Portable system* products are for indoor and outdoor use. The battery and the LEDs are housed in a single unit. The solar module is separate and can be placed outside for charging. *PSHS* products are mounted permanently in the home and are characterized by having the battery and the light source(s) contained in separate units. The solar panel remains in a fixed location and charges a battery unit housed indoors.

Field Study Details

The OGL users we studied in detail were night market vendors in two Kenyan towns: Mai Mahiu and Karagita. Detailed descriptions of the users and the study approach and the primary results are available in other works (Radecsky et al. 2008; Johnstone et al. 2009; Alstone et al. 2013). Both towns are relatively small (<10,000 people at the time of the study) and located in the Rift Valley Province. Before our study, the vendors relied primarily on kerosene lanterns to illuminate their nighttime businesses. We surveyed 50 vendors to establish baseline fuel-use trends and carefully measured baseline lighting fuel use for a subset of 23 vendors who were amenable to participating in the longer study and maintained a consistent shop location that allowed our survey team to visit night to night for measurements of fuel consumption. We then offered an opportunity to purchase an LED light with and without a solar charging option to the 23 for whom we had established a detailed baseline; 14 chose to purchase an LED lighting product and 11 consistently used it at their place of business (the other three used the lamp at their household). We tracked kerosene use, user satisfaction, and expenditures for lighting for all 23 vendors over a 1-year period.

Estimates of Embodied Energy in Off-Grid Lighting Products

Calculating embodied energy is a type of LCA that tends to follow one of two methods: economic input-output (EIO) models (Lave et al. 1995) and material processing models (Duque Ciceri et al. 2010). Economic models for estimating embodied energy are based on typical economic energy intensities (e.g., MJ/$) for the industry that manufactures each component or system. Material processing models use a bottom-up accounting process to estimate the primary energy requirements based on physical quantities for each part (e.g., MJ/W for a particular solar cell or gram of processed aluminum) and process (e.g., MJ per kilogram of plastic for injection molding).

We use material processing to estimate embodied energy because it is more able to differentiate among specific lighting systems and enable product designers to identify improvements. Economic embodied energy estimates for a specific product are less likely to be accurate as a result of the coarse nature of industry-wide economic energy intensity estimates and the very specific class of products we are considering (Lave et al. 1995). By choosing materials processing, we introduce the risk of choosing an outlier or inappropriate value for a particular material and truncation error from the choice of a boundary for the analysis (Lenzen 2000; Williams et al. 2009), but posit that they are outweighed by the benefit of insights from having estimates for specific inputs and processes instead of only sector-wide precision.

Material processing estimates of embodied energy depend strongly on the system boundary (Hammond and Jones 2011). In this report, our target boundary is “cradle to consumer,” meaning that we include raw material procurement and processing, intermediate transportation, manufacturing, packaging, transportation, warehousing, and distribution energy. Note, however, that we do not include end-of-life (EOL) energy requirements (which are currently minimal in practice, given the relatively low levels of waste management infrastructure and systems in many developing countries) or potential recycling/reuse of the materials.

To estimate embodied energy for each product, we performed a tear-down analysis on the lamp, solar module, and grid recharger. After disassembling each product into its constituent components, we measured the quantity or mass of each and accounted for production processes and transportation to market. We used similar approaches for fuel-based lamps, which use far simpler construction typically (sheet metal and sometimes glass).

In the spirit of Duque Ciceri and colleagues (2010), one goal of this analysis is to provide a freely available resource for others to estimate the embodied energy in OGL products. The full data set on embodied energy we compiled is available in the Supporting Information on the Web; it is tailored for OGL product-embodied energy estimates.

Lamps in this Study

The lamp we offered during the 2008–2009 study (pictured in figure 2A below) was based on a commercially available

LED task light (pictured in figure 2b below) and included the same main components, in addition to custom data logging circuits (the reason for the custom housing). Our embodied primary energy estimates for the field study are based on the commercially available version. The broken-down lamp and grid recharging circuit for the field study lamp are shown in figure 3. We assume that the kerosene offset by the commercial lamp would be the same as offsets by the modified unit we offered for sale because their functionality is the same and they share key components and circuits.

For the broad market analysis, we considered seven commercially available (as of summer 2012) products that had met the Lighting Global minimum quality standards.[3] A summary of their specifications is shown in table 1 along with those for the other products (including fuel-based lighting products). All the 2012 LED products, except for *DL B*, have mobile phone charging capability. Products *Mid C*, *Mid E*, *PSHS F*, and *PSHS G* include adapter kits for mobile phones, whereas the other products require the end user to supply the adapter cable. Some products also included a variety of other accessories, such as light stands, mounting hardware, extension cables, and/or other auxiliary charging kits. Our analysis of embodied energy includes all components included with each product. All of the products are made in China.

The fuel-based lighting technology listed in table 1 is described in more detail in the Supporting Information on the Web and other works (Radecsky et al. 2008; Alstone et al. 2013). Note that the lowest-service-level modern lighting systems (the 2008 field test and 2012 desk lamps) provide on the same order of bulk lighting service in terms of lumen-hours provided for each typical day of solar charging, compared to kerosene lamps in typical use.[4] Portable and PSHS provide substantially higher levels of service.

Use-Phase Energy Consumption

We estimate the use-phase primary energy consumption for fuel-based lighting and rechargeable OGL with a combination of survey data, baseline fuel consumption statistics, and lab measurements. The upstream emissions from fuel production are included in these estimates (details in the Supporting Information on the Web).

Baseline fuel consumption patterns for the field study were collected directly using a combination of successive mass measurements for lamps in use, record keeping on fuel purchases and duration of use, and observation (Alstone et al. 2013).

For the broad analysis, we use survey data from five countries ($n = 1{,}000$/country) in sub-Saharan Africa in 2008 (Baker and Alstone 2011). We estimate postadoption fuel consumption using heuristics developed in the field study and augmented by discussions with experts, anecdotal and published outcomes, and the authors' experience.

For grid-rechargeable LED lights that were deployed in the field study, we account for the energy consumed to produce power on the margin in Kenya, the measured performance of the recharging system, and observed patterns of use in the field.

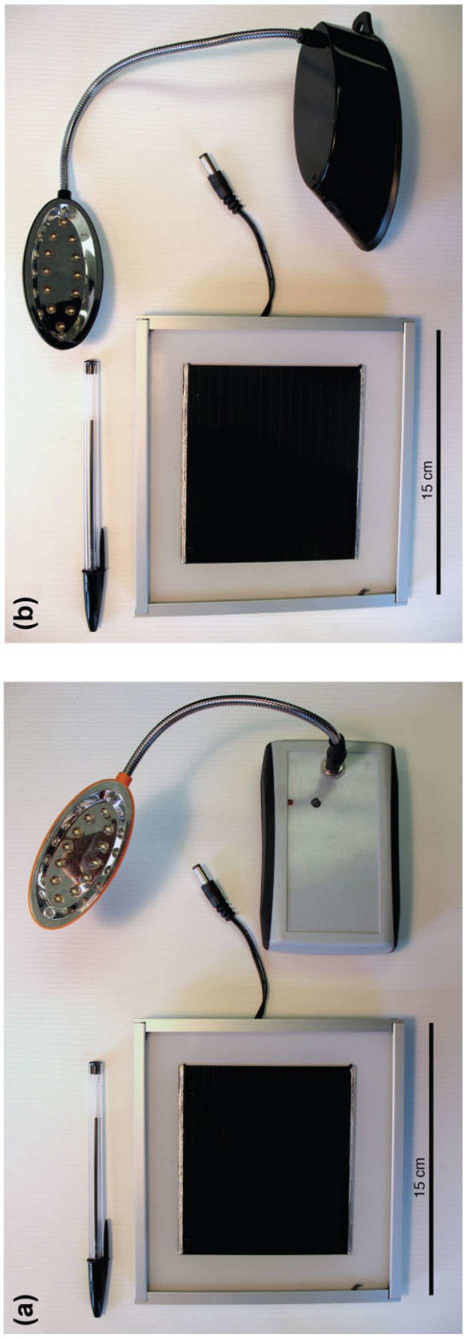

Figure 2 (a) The gooseneck lamp we offered for sale in Kenya with a 1 watt copper indium selenide solar module. (b) A commercially available gooseneck lamp that was the basis for the lamp we sold. It has the same internal components. The pen and a 15-cm solid line are included for scale.

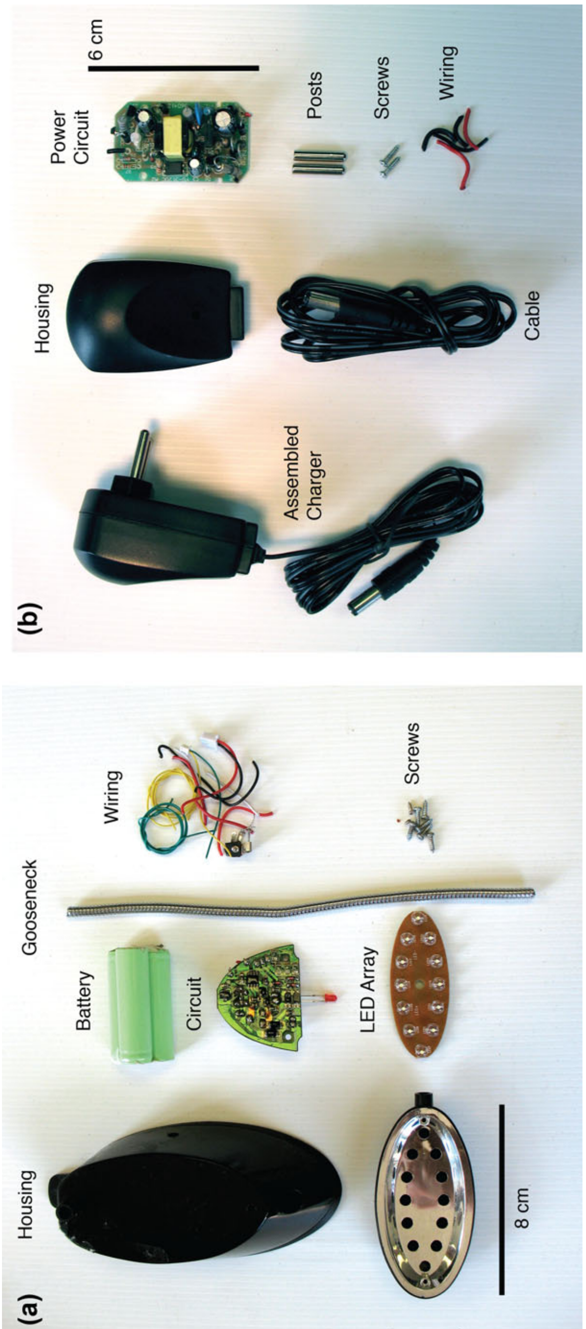

Figure 3 (a) Broken down LED lamp. (b) Broken down grid recharging circuit. LED = light-emitting diode.

Life Cycle Performance

Offsets of use-phase energy are the basis for determining the rate of *simple energy payback period* for pairs of new and incumbent technology (i.e., we compared the marginal daily decrease in primary energy consumption for use of lighting to the embodied energy for manufacturing the product).

Considering the EROI provides a better comparison between off-grid LED lighting and other clean energy technology interventions than energy payback period alone because it accounts for differences in lifetime. Our working assumption is that present-day commercial LED lamps have a lifetime of approximately 2 years, based on our extensive lab-based testing of OGL products (Mills and Jacobson 2007) and ongoing observations we made in the field-of-use patterns and the rigors of actual use. All the estimates in this study (except in a sensitivity analysis) are based on a 2-year lifetime.

EROI is the ratio of lifetime fuel savings (paybacks) to embodied energy (investments). An EROI of 1 is "break even," and below 1 is a worst-case situation that represents a net increase in worldwide primary energy consumption. We estimate EROI according to equation (1) below; note that this is subtly different from the EROI estimates commonly made for fossil fuels (FFs), which compare fuel delivered to end uses to the fuel production supply-chain energy. In this case, we compare the primary energy offset over the lifetime of an off-grid power system to the primary energy used to produce it.

$$EROI = {}^{E_{offset}}\!/\!{}_{E_{embodied}} \ \ or \ \ {}^{T_{lifetime}}\!/\!{}_{T_{PBP}} \tag{1}$$

where:

$EROI$ = energy return on investment (ratio)
E_{offset} = offset energy over the lifetime of the lamp (Joules)
$E_{embodied}$ = embodied energy to produce the lamp (Joules)
$T_{lifetime}$ = lifetime of product (years)
T_{PBP} = energy payback period of product (years)

Note that one can convert between EROI and energy payback period if the product lifetime is known by recognizing that the ratio between offset energy and embodied energy is the same as the ratio between the overall project (or product) lifetime and the energy payback period (proof in the Supporting Information on the Web).

Life cycle efficacy is calculated by combining an expectation of delivering lighting service—a number of lmhr—over a product lifetime with the lifetime primary energy requirement (MJ), including energy consumption in the supply chain and during use. With appropriate dimensional analysis, this relationship reduces to lm/W, the common measure of efficacy for light sources in the use phase.

There is always some degradation in light output over the lifetime of LED sources ("lumen degradation") that leads to a subsequent gradual decrease in life cycle efficacy. This phenomenon is ignored in our analysis, but could be incorporated in future work. The typical degradation over a service life of good-quality products is no more than 20% to 30% (and often is negligible), so the maximum average error over a product lifetime introduced by this omission is on the order of 10%.

Table 1 Product summary for LED and fuel-based lamps included in the study

Product ID code	*Category*	*Description*	*Service provided (lm-hr/day)*	*Year*
		2008–2009 field study		
Field Sol	LED	Barefoot firefly 2008 + CIS solar module	80	2008
Field Grd	LED	Barefoot firefly 2008 + AC/DC charger	80	2008
Field Hurr	Fuel	Dietz kerosene lamp used by night market vendor in Mai Mahiu; 50% offset fraction	100	2008
		Broad market analysis		
DL A	LED	Anonymous solar desk lamp	150	2012
DL B	LED	Anonymous solar desk lamp	30	2012
Mid C	LED	Anonymous mid-size solar portable	710	2012
Mid D	LED	Anonymous mid-size solar portable	350	2012
Mid E	LED	Anonymous mid-size solar portable	350	2012
PSHS F	LED	Anonymous PSHS	2,500	2012
PSHS G	LED	Anonymous PSHS	2,800	2012
Wick 100	Fuel	General wick lamp (100% offset fraction)	40	c. 2010
Hurr 100	Fuel	General hurricane lamp (100% offset fraction)	100	c. 2010
2x Hurr	Fuel	Two general hurricane lamps (100% offset fraction)	200	c. 2010

Note: Service estimates are based on detailed laboratory testing in the case of LED products (conducted through the Lighting Africa program) and on the best available estimates for service from fuel-based lighting. Details on the estimates for fuel-based lighting are included in the Supporting Information on the Web.

LED = light-emitting diode; CIS = copper-indium-selenium (type of solar cell); AC/DC = alternating-current to direct/current adapter; PSHS = pico solar home system.

Error Analysis

Accounting for uncertainty is a critical element for any LCA, particularly if the results will be used by guide policy decisions (Lloyd and Ries 2007). We approach uncertainty in this work using Monte Carlo techniques by assuming that each value in the analysis has a central estimate with lower and upper bounds that define a triangular probability distribution of likely true values. In some (rare) cases, the lower and upper bounds are defined in the sources for energy intensity of materials and processes; for those sources that do not estimate uncertainty themselves, we assume the basic deviation from the central estimate is ±40% for peer-reviewed articles and databases, ±45% for government-sponsored reports, ±60% for conference papers and industry-sponsored reports, and ±75% for values from presentations that do not have a supporting report. We account for ongoing energy use for continued fuel-based lighting and/or recharging with grid power in a similar way, with triangular distributions around a central estimate.

Results and Discussion

Baseline Emissions and Offsets from Improved Lighting

In the field study, we found that after adopting improved lighting the average reduction in use of the baseline technology—hurricane lamps—was to 50% of the baseline (Alstone et al. 2013). People who did not eliminate kerosene use tended to have larger businesses that were underserved by their baseline lighting and would have also been underserved by a single improved light, so they employed both technologies (Alstone et al. 2010). Though many products allow people to completely eliminate kerosene, an average offset of 50% is not outside the norm depending on the class of product; Brüderle (2011) reported kerosene offsets for a range of products from 30% to 100%, with several at approximately 50%. The lower-performance products tended to have lower offset fractions, as one would expect. A recent Web forum discussion on the topic indicated similar variable findings across a range of experiences and contexts by practitioners and researchers (LuminaNET Contributors 2013).

The users in the 2008–2009 field study uniformly chose to use grid recharging (vs. solar), with a median daily requirement of 0.05 MJ of primary energy to generate the required electricity based on the observed frequency of lamp recharging, the Kenya grid mix, and measured efficiency of the charging system. It is notable that these users were paying fees for recharging (typically approximately US$0.25 every 3 days) that would easily have been recouped with purchasing a solar module, but people preferred the "convenience and security" of recharging on the grid (Alstone et al. 2013). This was a special case compared to household and private businesses, in some ways because of the public location of these business users, and does not reflect the broad market for solar-charged OGL products (Dalberg Global Development Advisors 2013).

For the broader analysis, we use baseline estimates for the typical fuel consumption in hurricane and wick lamps from Baker and Alstone (2011), a five-country market research study that included questions on fuel consumption from 1,000 representative users in each country (Ethiopia, Ghana, Kenya, Tanzania, and Zambia). The mean monthly expenditure for

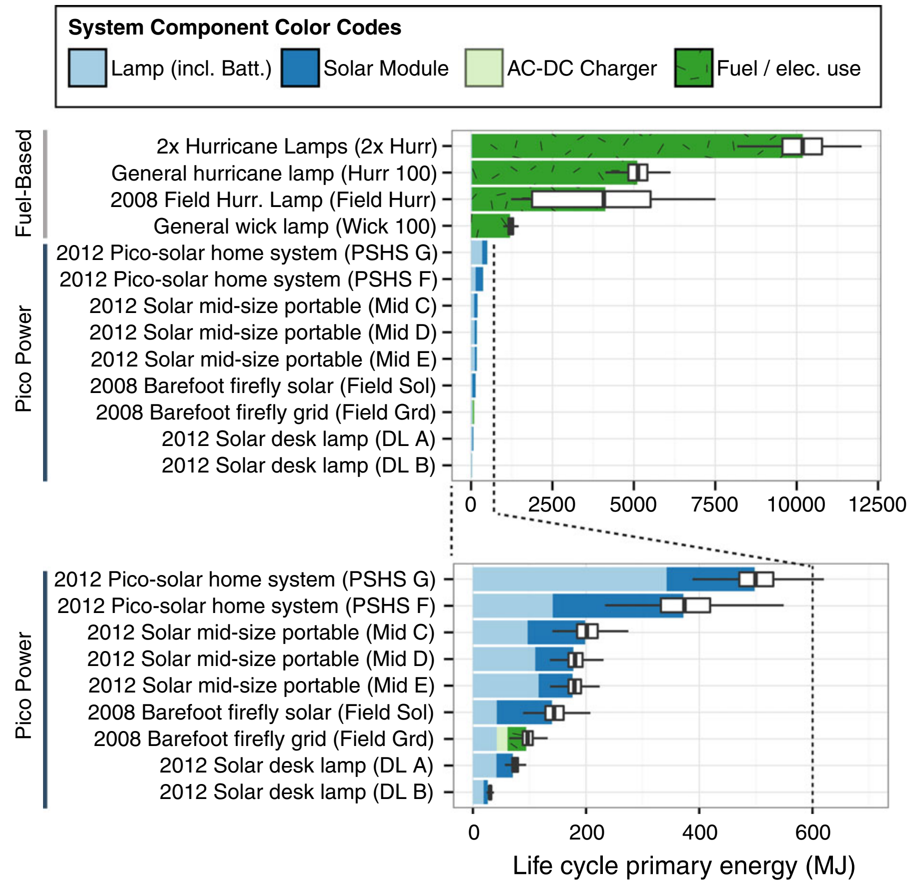

Figure 4 Primary energy requirements for all the products over a 2-year period in both studies (top) and a zoomed view of only light-emitting diode lighting products (bottom). Energy for all phases is included for each product, but the manufacturing phase energy for fuel-based lights is only barely visible because it is very small (<50 megajoules [MJ]), compared to the fuel used. Box plots indicate the median, interquartile range (box), and 90th percentile range (whiskers). Fuel and electricity estimates are for single individual users over a 2-year period. Box plot and results for the "Field Hurricane" lamp are direct results from the field for a specific population in rural Kenya (as described elsewhere); the rest of the estimates are based on the life cycle energy accounting estimates. The product descriptions that correspond to each product referenced here can be found in table 1.

hurricane lamps is US$5.05 (n ~ 2,200 users with a range of in-country means from US$3 to US$8) and for wick lamps is US$1.19 (n ~ 1,400 users with a range of in-country means from US$1 to US$5). Taking a rough cost of US$1/liter for kerosene (Radecsky et al. 2008; Tracy and Jacobson 2012; Alstone et al. 2013), the average daily energy use is 7.0 and 1.7 MJ, respectively, including upstream emissions from kerosene production. Details are in the Supporting Information on the Web.

Based on our field experience and reported results from other researchers (Brüderle 2011), we expect that the various classes of pico power product will offset different levels of kerosene consumption based both on their suitability as a replacement and the expected consumption patterns for end users of varying income (where richer end users are more likely to be able to afford higher-performance pico power products and more likely to be using more kerosene before adopting them). The heuristic for this analysis is that desk lamps replace a single wick lamp (similar in consumption rate to 50% of a hurricane lamp), portable lights that are higher performance will replace a full hurricane lamp, and PSHSs with multiple lighting points will replace two hurricane lamps.

Embodied Energy for Off-Grid Lighting

The total life cycle energy use for each of the lighting technology types is summarized in figure 4. The details of the estimates, including each element of the embodied energy calculation for the "field" lamps, are provided in the Supporting Information on the Web. The embodied energy for manufacturing hurricane and wick lamps is very low, at 26 and 1 MJ, respectively (and is barely visible on the chart). However, the use-phase energy requirements are substantial for fuel-based lighting, dwarfing the embodied energy for manufacturing LED lighting systems, which ranges from 25 to 500 MJ.

The products with larger fractions of embodied energy attributable to solar panels have greater uncertainty because the small size of OGL solar (0.5 to 5 W), compared to grid-connected, modules (150+ W) necessitates the use of an

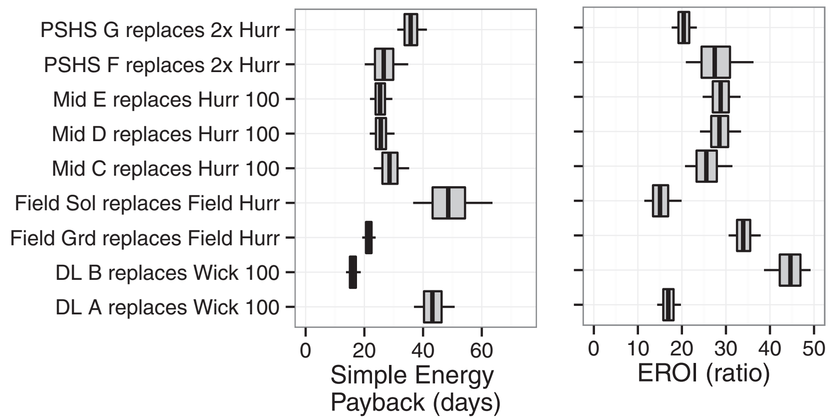

Figure 5 Simple payback and energy return on investment (EROI) for combinations of improved lighting and fuel-based lighting being replaced (all assume a 2-year lifetime). Box plots show the interquartile range (box) and 90th percentile range (whiskers). The product descriptions that correspond to each product referenced here can be found in table 1.

uncertain scaling factor to account for the differences in frame-to-area ratio and assembly (details in the Supporting Information on the Web).

As a point of comparison, we completed a preliminary economic-based estimate for embodied energy for each of the 2012 LED products using a freely available Web tool (Carnegie Mellon University Green Design Institute 2013). Estimates are well correlated with our materials processing values, but are approximately three times higher. This suggests potential for using economic estimates as a proxy for materials processing estimates with some correction factor, or that the system boundary we chose was too small to capture the full economy energy dynamics for the products (details in the Supporting Information on the Web).

Energy Payback and Return on Investment for Off-Grid Lighting

Both solar- and grid-charged LED lamps have fast energy payback periods considering the amount of avoided kerosene among adopters of LED lighting. Figure 5 summarizes the estimates for simple energy payback and EROI across a range of expected substitution combinations. The range is 20 to 50 days for energy payback time and 10 to 40 for EROI ratios. Payback time values are well within the anticipated product service lives.

Off-grid LED lighting has a surprisingly fast energy payback period compared with other solar applications. Both grid- and solar-charged LED products appear to have substantially faster energy payback than kilowatt-scale, grid-connected solar photovoltaic systems, which have been the subject of several LCAs and have payback periods ranging from 0.5 to 5.5 years, depending on the technology and location (Fthenakis and Alsema 2006; Alsema and de Wild-Scholten 2006; Raugei et al. 2007).

However, a key point is that OGL lifetimes are shorter than solar-electric systems in general. Because they are integrated systems, the failure of a single component, such as the battery, can lead to EOL unless it is easily replaceable. Also, as with other consumer electronics, OGL may be subject to greater mechanical stress (e.g., being dropped) than is typical for solar electric systems and more environmental exposure to water and dust than typical in-home appliances. Moreover, cost pressures can also lead to production of inferior, short-lived products in the absence of clear information on product quality.

Even with short lifetimes, OGL offers as good or better EROI as large grid-connected renewable energy systems and oil production. Based on our estimates, which are for a specific LED lamp in a particular context, approximately 1 to 3 months of the 2-year estimated product lifetime are devoted to paying energy debt with EROI of 10 to 40. As mentioned above, grid-connected solar electric systems have 0.5 to 5.5 years of a 25-year lifetime devoted to energy debt—between 2% and 22% of the lifetime—resulting in EROI of 4.5 to 50. This places off-grid LED lights' EROI among those of grid-connected solar electric systems, and approximately equal to that of wind energy systems, which have an average EROI of approximately 20 based on a meta-analysis of operational wind generation projects by Kubiszewski and colleagues (2010). Oil production also has similar EROI (on the order of 10 to 20), albeit under a slightly different (but still roughly comparable) definition, as noted above (Guilford et al. 2011).

It is possible that truncation errors in our estimates for embodied energy lead to longer payback periods and worse EROI. However, even if the embodied energy estimates were off by a factor of 3 (the "EIO-LCA" estimate), the results would still be quite positive with payback periods of 0.25 to 1.0 year and EROI of 2 to 10.

Figure 6 shows the expected range in EROI depending on the amount of fuel use that is offset and the product lifetime for a hypothetical solar LED lighting system. In this example, there are 140 MJ of embodied primary energy and the product is being used by someone who previously used 5 MJ of fuel each night for

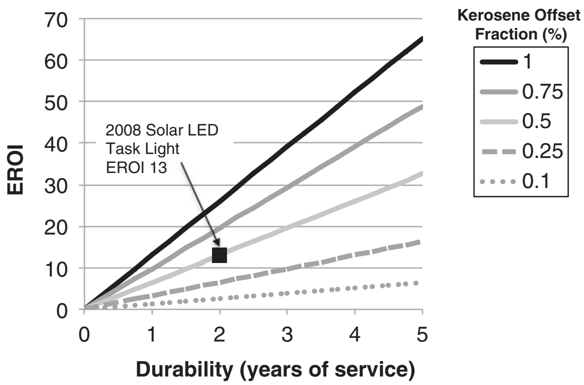

Figure 6 Energy return on investment (EROI) for an LED lighting system with 140 megajoules (MJ) of embodied energy that is used by someone with baseline fuel use of 5 MJ/day as a function of durability (with years of service as a proxy variable) at various kerosene offset fractions (the fraction that is offset by adoption of the modern light). An example product is shown with a black square based on observations from the field in 2008. LED = light-emitting diode.

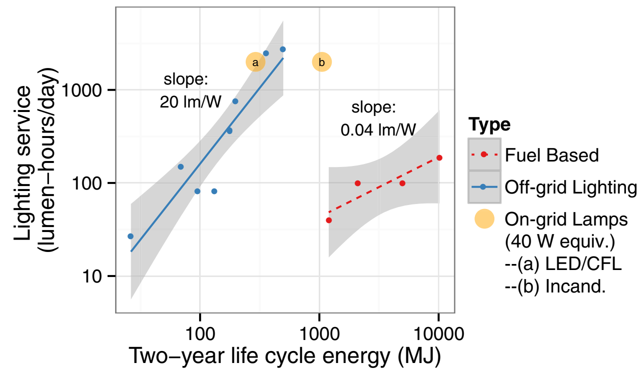

Figure 7 Log-log scatterplot of daily lighting service vs. two-year life cycle energy use for products in both phases of the study with comparisons to on-grid lamps. Simple linear models are fit through both fuel-based and off-grid lighting products and the 95% confidence interval for the average is shaded in grey. The slopes are indicated with units converted to lumens per watt (lm/W). The on-grid lamps provided for comparison are based on 2012 estimates for life cycle efficacy of energy efficient (LED or CFL) bulbs and the baseline incandescent technology (Navigant Consulting 2012). The on-grid estimates are shown as "40 watt equivalent" that provide about 500 lumens of light for 4 hours a day. LED = light-emitting diode; CFL = compact fluorescent lamp; Incand. = Incandescent.

lighting—a very similar situation to the one we observed in the field. An example that is similar to what we observed in the field in 2008 is noted on the plot corresponding to an EROI value of 13, which corresponds to a 2-year service lifetime at an offset fraction of 0.5 for the hypothetical product. At the low end on the figure is an LED light that only lasts 6 months and offsets 10% of the baseline fuel use, resulting in a very low EROI of 0.65. On the other hand, a system that offsets 100% of lighting fuel and lasts 5 years will have a greatly improved EROI of nearly 65, which is not out of the question with current technology and manufacturing options (i.e., with highly efficient LEDs, long-lasting lithium chemistry batteries, good-quality solar and balance of systems, and 5 years of experience manufacturing products).

Life Cycle Efficacy for Off-Grid Lighting

The driver of the fast-energy paybacks and large returns for improved OGL is the significantly higher life cycle efficacy of LED lights with continuing rapid improvements, compared to kerosene and other flame-based light sources. LED light sources are improving in source efficacy and the best among them are now better than the best available fluorescent tube lighting at 120+ lm/W (converting electricity to light). The performance improvement trend for LEDs is steep and the technology is expected to approach 200 lm/W over the next decade (Azevedo et al. 2009; USDOE 2013). As a point of reference, the efficacy of unpressurized fuel-based lighting is reported to be roughly 0.1 lm/W (converting liquid fuel to light) in estimates from other studies (see the Supporting Information on the Web).

Figure 7 shows how the performance differences between fuel-based and LED lighting play out in the context of this study by comparing lighting service to the life cycle primary energy required to obtain it. The slope of each linear fit, with appropriate scaling, yields the typical life cycle efficacy for each lighting system type. We find that typical OGL systems achieve approximately 20 $lm/W_{primary}$ and fuel-based lighting has a life cycle efficacy of approximately 0.04 $lm/W_{primary}$, or 500 times less efficient. These estimates are very similar to the estimates reported by Durlinger and colleagues (2012) (after converting their estimates to $lm/W_{primary}$ from the reported units [kg oil-$_{equiv}$/109,500 lm-hr]). The average OGL system in their analysis was 20 $lm/W_{primary}$, and the average kerosene lamp was 0.08 $lm/W_{primary}$.

The life cycle efficacy of OGL systems in 2012 is similar in magnitude to efficient on-grid lighting. A U.S. Department of Energy (USDOE)-sponsored LCA for AC grid-powered lamps in 2012 has results that lead to estimates of the life cycle efficacy of LED and CFL bulbs (after adjusting from the originally reported units) at 18 $lm/W_{primary}$ and incandescent and halogen at 5 $lm/W_{primary}$ (Navigant Consulting 2012). LED improvements are expected to raise the life cycle efficacy for on-grid bulbs to 40 $lm/W_{primary}$ by 2015.

Our results indicate that off-grid LED products are very similar to grid-powered bulbs on a life cycle efficacy basis, but the off-grid alternative (0.04 $lm/W_{primary}$ fuel-based lighting) is approximately 100 times worse than the on-grid one (5 $lm/W_{primary}$ incandescent lighting). This disparity in service alternatives highlights the critical need to support adoption and markets for off-grid high-efficiency lighting. As the efficacy of LEDs and durability of products improves, the life cycle efficacy will improve as well, offering even more lighting service to the global poor for the same primary energy investments.

Economic and Environmental Sustainability

Good-quality OGL is not only a good energy investment, but also pays back on economic terms—a critical factor for often cash-poor buyers and users. The participants in our 2008 study paid market rates (approximately US$10) for grid-charged OGL products and saved approximately US$0.10 per day, compared to those who did not adopt LED lighting (see the Supporting Information on the Web). Their simple payback was approximately 100 days, and the financial return on investment (with the same structure as EROI presented above) was approximately 10. These indicators are not as favorable as the energy return indicators resulting from imperfect correlation between energy intensity and cost, particularly if the buyer acts with a high discount rate for future savings, and suggests a potential for using financial tools to support OGL products so that the investment end users are asked to make is on similar terms as the energy investment being made in the industrial economy. Access to financing that allows buyers to spread out payments for what is a relatively large capital purchase has been recognized as a critical factor for reaching high levels of access to modern lighting and driving the growth of the market (Baker and Alstone 2011; Dalberg Global Development Advisors 2010; Alstone et al. 2011; Intellecap 2012).

Saving primary energy is not a goal in itself, but is tracked because it is related to direct reductions in harms to the climate and public health. Adopting improved lighting in sub-Saharan Africa with lamps imported from South Asia means offsetting large levels of future FF combustion in African households (that were extracted and refined in the global oil market) for small increases in the current-day energy consumption for global supply chains and factories with a concentration in South Asia—effectively shifting emissions in both time and space. The work presented here can be extended by translating the energy requirements for globally distributed lighting systems to local and global emissions burdens. Focused regional impacts such as BC GHG forcing and public health risks from particulate matter should be accounted for based on the source type and location of emissions, whereas well-mixed GHG, such as carbon dioxide, are not as important to track spatially, unless carbon credits or emissions fees are involved.

We identified two key factors that determine energy, economic, and environmental performance of OGL products: durability and performance. Products that are more durable last longer, stretching the payback on energy terms. Higher-performance products will lead to greater fractions of kerosene offset. However, in order for any of these benefits to be realized, end users and other buyers must be convinced of the quality and performance for products. There was a wide range of quality for products available in the market in 2012 (Harper et al. 2013) and identifying and communicating reliable quality and performance information is critical to continued development.

The EOL for improved OGL products will be an important issue as the first generations of products fail and are replaced and/or discarded. Designing for EOL reuse, reengineering, or recycling (Hendrickson et al. 2010), eliminating the use of acutely toxic materials such as cadmium and lead (found in nickel-cadmium and lead-acid batteries), and building robust "reverse supply chains" to take back parts that cannot be reused are all important challenges to address for the nascent market.

Because LED lighting provides less-expensive, higher-quality services, it is reasonable to expect a degree of "energy rebound" as people adopt the technology because they sufficiently value the additional light (Borenstein 2013). This means consuming more light (measured in lmhr) than the fuel-based lighting baseline and a reduction in potential primary energy (and economic) savings, compared to direct substitution. The phenomenon has been documented using global historical data for industrialized regions (Saunders et al. 2010), is evident in the sales projections for OGL that include many lamps with higher performance than fuel-based lighting (Dalberg Global Development Advisors 2010), and is reflected in the priorities of end users who desire "more, brighter" light from improved OGL products (Alstone et al. 2013). However, the large discrepancies in life cycle efficacy between the technologies (20 vs. 0.04 $\mathrm{lm/W_{primary}}$) suggest that people would need to consume 500 times more light to completely eliminate life cycle energy benefits from OGL, a level well beyond the status quo for the initial adopters of OGL products,[5] but on the same order of magnitude as consumption levels in the industrialized world (Saunders et al. 2010). As LED chip efficacy continues to rise (USDOE 2013), driving up life cycle efficacy, the global long-term equilibrium consumption of lighting is likely to continue rising, both off and on the grid, among people with access.

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Notes

1. We use the term off-grid lighting (OGL) in this article to refer to a diverse, emerging set of products that are focused on meeting the basic energy needs of people with little or no access to grid electricity. These products are also variously referred to by others as solar lanterns, pico power product, micro energy devices, and so on.
2. Estimates based on functional units from previous works can be converted to life cycle efficacy with dimensional analysis.
3. The Lighting Global quality assurance program is associated with the Lighting Africa and Lighting Asia initiatives. These programs are affiliated with the International Finance Corporation (IFC) and World Bank.

4. A "standard solar day" is defined as 5 kilowatt-hours (kWh)/m^2/day and is representative of average daily insolation in tropical latitudes where many off-grid people live.
5. The highest-performance OGL products currently available in August 2013 have output "only" ~20× the output of a hurricane lamp based on third-party test data from Lighting Global's Standardized Specifications Sheet Program at www.lightingglobal.org/specs (Lighting Global 2013).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information includes the following: publicly available embodied energy intensities (appendix S1); details on embodied energy estimates (appendix S2); notes on the relationship between energy payback period and EROI (appendix S3); details on the broad market analysis (appendix S4); comparison with EIO-LCA (appendix S5); fuel-based lighting technology (appendix S6); and next steps (appendix S7).