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From carbon to light: a new framework for estimating greenhouse gas emissions reductions from replacing fuel-based lighting with LED systems

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Abstract There is considerable well-intended, yet wishful anticipation about reducing greenhouse gas emissions by replacing fuel-based lighting in the developing world with grid-independent light-emitting diode (LED) lighting systems. Most estimates gloss over important practical realities that stand to erode a genuinely significant potential. The Clean Development Mechanism (CDM) is the leading system for quantifying the benefits of such projects in developing countries and embodying them in a market-based platform for trading carbon credits. However, compliance with methodologies for highly decentralized, small-scale energy saving projects currently employed in the CDM is viewed by developers of as onerous, time-consuming, and costly. In recognition of the problem, the CDM has recently placed priority on improved methodologies for estimating carbon dioxide reductions from displacement of fuel-based lighting with energy-efficient alternatives. The over-arching aim is to maintain environmental integrity without stifling sustainable emission-reduction projects and programs in the field. This article informs this process by laying out a new framework that shifts the analytical focus from highly costly yet narrow and uncertain baseline estimations to simplified methods based primarily on deemed values that focus on replacement lighting system quality and performance characteristics. The result—many elements of which have been adopted in a new methodology approved by the CDM—is more structured and rigorous than methodologies used for LED projects in the past and yet simpler to implement, i.e., entailing fewer transaction costs. Applying this new framework, we find that some off-grid lighting technologies can be expected to yield little or no emissions reductions, while well-designed ones, using products independently certified to have high quality and durability, can generate significant reductions. Enfolding quality assurance within the proposed framework will help stem "market spoiling" currently underway in the developing world—caused by the introduction of substandard off-grid lighting products—thereby ensuring carbon reduction additionality (emissions reductions that would have not occurred in the absence of the CDM program).

Keywords Clean development mechanism · Energy efficiency · LED lighting · Carbon emissions · Developing countries

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Introduction

One in four people on Earth lack electricity, deriving illumination for their homes—and often their businesses—from the flame.[1] According to the International Energy Agency, in the absence of serious intervention, this number will decline only slightly over the following two decades and will in fact *rise* significantly in sub-Saharan Africa (World Energy Outlook 2009).

While off-grid lighting users spend nearly $40 billion per year (almost 20% of all global lighting expenditures) on ad hoc and polluting methods for obtaining illumination, they receive only 0.1% of the total lighting services consumed by the electrified world (Fig. 1). The carbon dioxide emissions emitted in producing this inferior illumination are equivalent to that of about 30 million cars.[2]

As such, the primary by-product of illuminating non-electrified homes and businesses in the developing world with fuels is greenhouse gas emissions and only secondly light. This state of affairs contributes to poverty as well as to global warming. Other adverse impacts include suppressed productivity when fuel-based lighting is used in market or production contexts, adverse effects on health through burn risks and indoor air pollution (Apple et al. 2010),[3] poor reading conditions, excessive costs for unelectrified businesses, and reduced nighttime security. With a combination of new technologies and appropriate market-delivery solutions, this situation can be reversed to a profound degree.

The single-most promising of these new technologies are solid-state light sources that emit white light, or, as they are more commonly known, light-emitting diodes (LEDs; Mills 2005; Lighting Africa 2010). LEDs offer many attributes that are superior to or otherwise provide a more appropriate fit to developing-country lighting needs than fluorescent lighting technology—which, prior to the advent of LED lighting, has been rightfully promoted as the best way to improve efficiency in comparison to traditional incandescent or fuel-based light sources.

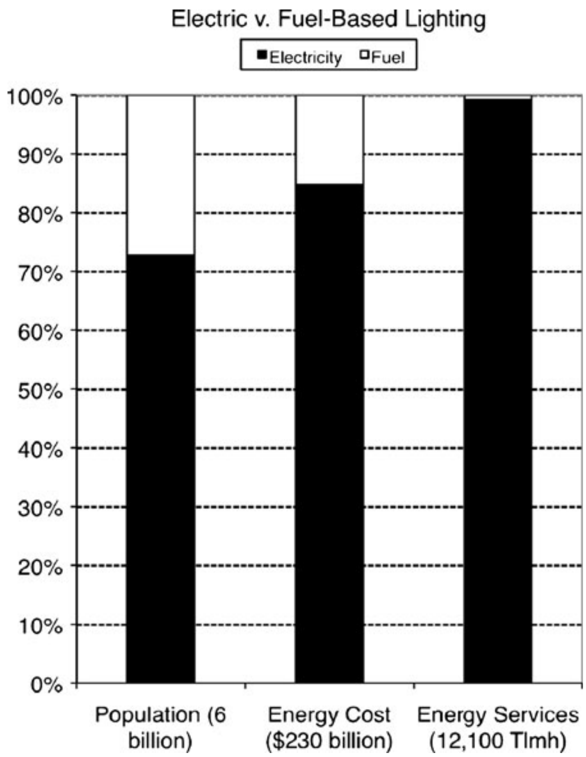


Fig. 1 Lighting cost and services for electrified and un-electrified populations (Mills 2005)

Properly applied, the additional energy savings from LEDs compared to fluorescents can be on a par with those historically gained through the conversion from incandescent to fluorescent lamps. LEDs also offer a number of other attributes that are highly desirable in a developing-country context, including: long service life, ruggedness, absence of mercury, low-voltage operation, compact/portable size, and a form factor well-suited toward directing light on the required task with very high optical efficiencies.

Although diffuse compared to lighting markets in the industrialized world, the existing fuel-based off-grid lighting market is present in nearly 200 countries and has an established distributed energy delivery system (typically kerosene).

Low-income consumers in developing countries have demonstrated the ability to adopt new lighting technologies rapidly. For example, 90% of flashlights in parts of Kenya are now based on LEDs (Johnstone et al. 2009). Properly designed and manufactured, a wide diversity of LED lighting systems could displace

[1] This article builds on Mills (2010).

[2] At US average conditions of approximately 20,000 vehicle kilometers traveled per year at 0.81 l/100 km.

[3] Note that many proponents of off-grid lighting conflate the documented health impacts and mortalities associated with fuelwood with those from lighting. However, while cook stoves no doubt pose a far greater threat to health and life than do lighting fuels, those from lighting are not trivial.

large quantities of kerosene lighting. This shift could be driven by dramatically lower operating costs and a host of other end-user benefits. The efficiency of fuel-based lighting strategies can be as low as 0.04 lm/W or less than 1/1000th that of a modern LED light source. Put another way, a typical kerosene lantern consumes kerosene at a rate of approximately 200 W, while a quality LED-based lamp using 1 W of electricity produces five times the light output.

Eliminating and monetizing all greenhouse gas emissions associated with global fuel-based lighting would correspond to as much as a $4 billion annual market.[4] At the level of the individual consumer, the per-lantern value of the carbon offset could be a substantial fraction of the improved lantern's cost, providing a compelling impetus for large-scale market transformation.

The Clean Development Mechanism (CDM) has been instrumental in creating a massive and fast-growing market for carbon emissions reductions.[5] Governments of industrialized countries can use Certified Emissions Reductions (CERs) from CDM projects to fulfill their commitments under the Kyoto Protocol. Likewise, companies can use them in emissions trading systems like that introduced in the EU. The tradable emissions can be supplied by certified projects that improve energy systems in developing countries. The financing of projects that deliver CERs into these markets in theory overcome market barriers and failures that would otherwise thwart investment in low-emissions energy systems in the developing world.

Currently, however, CDM projects addressing small-scale emissions such as those in household lighting (on or off the electrical grid) are playing a vanishingly small role in carbon-trading markets (Michaelowa et al. 2009). This is due in part to the high transaction costs of attaining and documenting these savings in comparison to larger centralized projects such as those in the power or industrial sectors. Two proposed off-grid lighting projects (both in India) have recently been approved for CDM credits.[6] This article explores means for fostering increased activity via an improved and less onerous carbon-accounting methodology than those utilized by the CDM thus far.

Greenhouse gas emissions from fuel-based lighting

People without access to electricity grids (or distributed electricity generation) obtain light in a remarkable variety of ways. The predominant fuel is kerosene, but other ubiquitous sources include diesel, candles, various forms of biofuels, and battery-powered flashlights. Users commonly employ more than one type of fuel and consume them in various types of lamps (Fig. 2a–b). Patterns differ by country and at far smaller scales within countries. Each lamp–fuel combination results in a different carbon intensity (emissions per hour of utilization) and lighting service level. Figure 3 provides an example limited to a family of kerosene-burning lamps demonstrating differences in fuel-use rates and associated carbon emissions.

The single published global estimate of greenhouse gas emissions from fuel-based lighting places the value at 190 million metric tons of CO_2 per year (Mills 2005). This could well be an under estimate as it did not explicitly include biomass, other greenhouse gasses, or the global warming potential of associated black carbon ("soot"), which is not treated as a greenhouse gas under the Kyoto Protocol. Non-household uses were only roughly estimated, and results were not broken out by geography or demographic factors. The estimate is also built up from the nominally unelectrified population, whereas electrified households and businesses revert to kerosene during power outages, which are frequent in many areas. In a recent market test in Kenya, just over 25% of those who purchased LED lamps intended to replace kerosene lanterns occupied homes that were on the grid (Tracy et al. 2010a).

The intensity of use varies widely within countries and even specific demographics (Fig. 4a–b). A compilation of 28 surveys from around the world

[4] This amount derives from estimated carbon emissions of 190 MT CO_2/year (Mills 2005) at the current selling price of approximately US$20 per ton CO_2.

[5] While this article focuses on the CDM, the principles developed herein apply equally well to the various voluntary market emissions-reduction systems, and could in fact add rigor to such programs and thus increase the valuation of carbon offsets they attain.

[6] See http://cdm.unfccc.int/Projects/DB/TUEV-SUED1245158196.62/view and http://cdm.unfccc.int/Projects/DB/DNV-CUK1226479189.57/view.

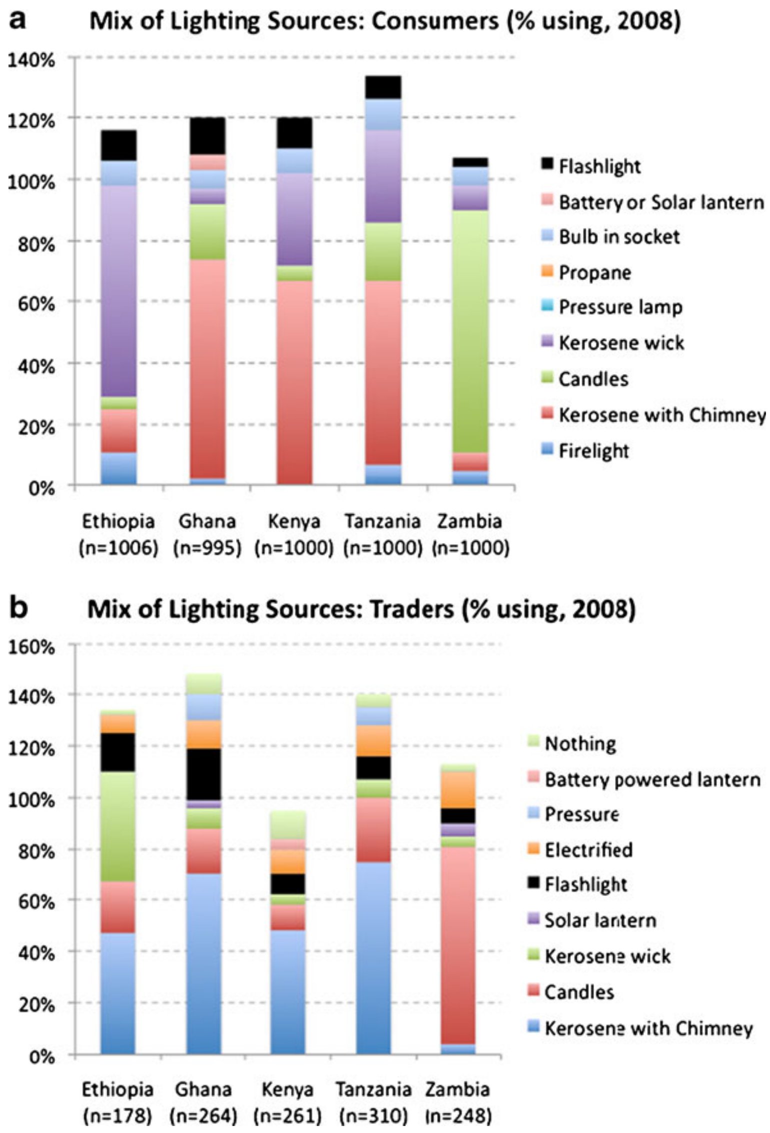


Fig. 2 a–b Wide variance in the types of lighting sources used by consumers and traders (night market vendors) in off-grid areas. These country specific data were collected by Lighting Africa (2009, 2011) through surveys of 2,831 consumers and 1,261 traders. In most cases, users employ more than one type of light source (totals > 100%). Consumer values are for light used the previous night

showed a variation of 3–30 l/month of lighting fuel use (Mills 2005). The drivers of these wide differences are not primarily attributable to geography.[7] For example, in Ghana (and no doubt elsewhere), some night vendors use lamps with very large wicks that consume fuel at the rate of 0.06 l/h. This use rate, combined with very long hours of use, results in annual fuel consumption of about 180 l/lantern as compared to approximately 20 l/lantern for ordinary households using conventional lamps for shorter periods of time each day.

In the case of non-renewable biomass, the amounts of net greenhouse gas emissions have not been quantified. Biofuel light sources include raw plant and wood fuels (from grass to resins), vegetable oil, biogas, yak butter, and animal oils. Highly resinous plants (e.g., the African Olive) are used exclusively for lighting. Wood cooking fires are used to an unknown degree for illumination globally, and at least in some contexts for this reason are burned longer than required for cooking. The degree to which these fuels are sustainably produced versus net carbon producers has not been quantified. Of the five countries surveyed by

[7] However, geography can be taken into consideration for things like baseline lighting fuel mix, prevailing fuel prices, and willingness to pay for alternative technologies.

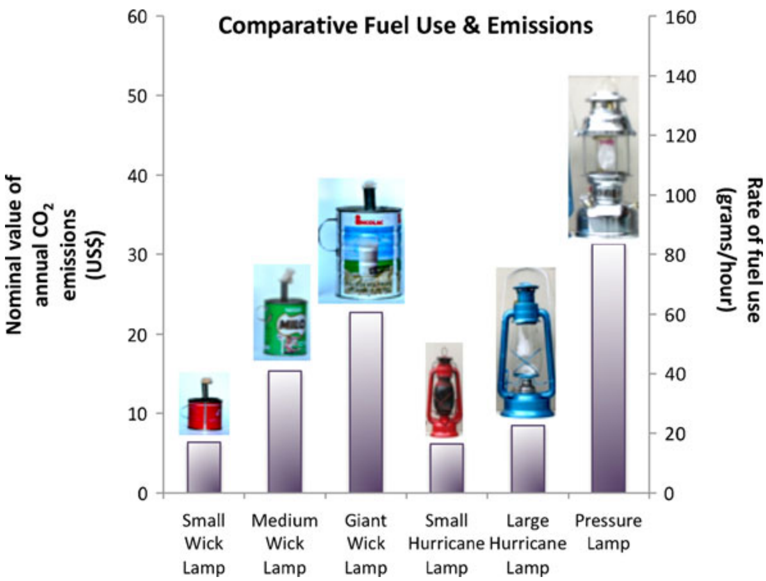


Fig. 3 Rates of fuel use vary widely among lamps. Those shown in this figure vary from 0.018 to 0.089 l of kerosene per hour. Annual estimates are based on 4-h/day use, a 5-year time horizon, an emissions factor of 2.4 kg CO_2/l, and an illustrative emissions price of $20/ton CO_2. Note that the vast preponderance of users fall into the small or medium wick or hurricane lamp categories, implying a factor of three variance in fuel-use rates. Source: Field measurements—timed using a digital balance—by Lawrence Berkeley and Humboldt State University (Lumina Project)

the Lighting Africa Project, half the households report using fuelwood daily for illumination, and two thirds report doing so two or three times a week (Fig. 5). As seen in Fig. 2a, nearly 20% of homes in Ethiopia report using these fuels for lighting (Lighting Africa 2009, 2011). The Tanzania household survey reports that 7% of rural households use firewood as a primary source of lighting, and the value runs as high as 24% in one district (National Bureau of Statistics Tanzania 2002).

The potential for LED replacement technologies

For multiple reasons, *properly designed and manufactured* LED lamps are vastly superior to the incumbent fuel-based lighting technology, as well as highly appealing alternatives to the nearest competing technology alternative (fluorescent or compact fluorescent lamps, CFLs):

- Unlike most other lighting technologies, which have matured and reached efficiency plateaus, LEDs for white light are relatively new and are undergoing rapid efficiency improvements and cost reductions.
- They are much more rugged and longer-lived than fluorescent lamps.
- They provide better quality illumination for certain tasks.
- At over 100 lm/W, LED peak efficiencies have already surpassed those of CFLs, and the US Department of Energy has set a target of 165 lm/W by the year 2025 (USDOE 2009).
- Low-power requirements mean that charging systems and batteries can be much smaller than those in conventional household solar electric lighting systems (e.g., AA size rechargeable batteries instead of batteries of similar size to those used in motorcycles and cars).
- A low-voltage platform is especially suitable for a solar power supply.
- Products are typically portable "integrated systems" (including lights, charging, and storage), requiring no assembly and, if well-made, relatively little maintenance in the field.[8]
- Grid-independent lighting systems are not subject to the risks of voltage fluctuation that have created

[8] The analysis in this report focuses on integrated systems. Custom-made LED lighting systems (e.g., with technician-installed batteries, lights, and charging devices) are not common in this market and the associated risks would need to be treated in the CDM assessment framework in much the same fashion as traditional Solar Home Systems.

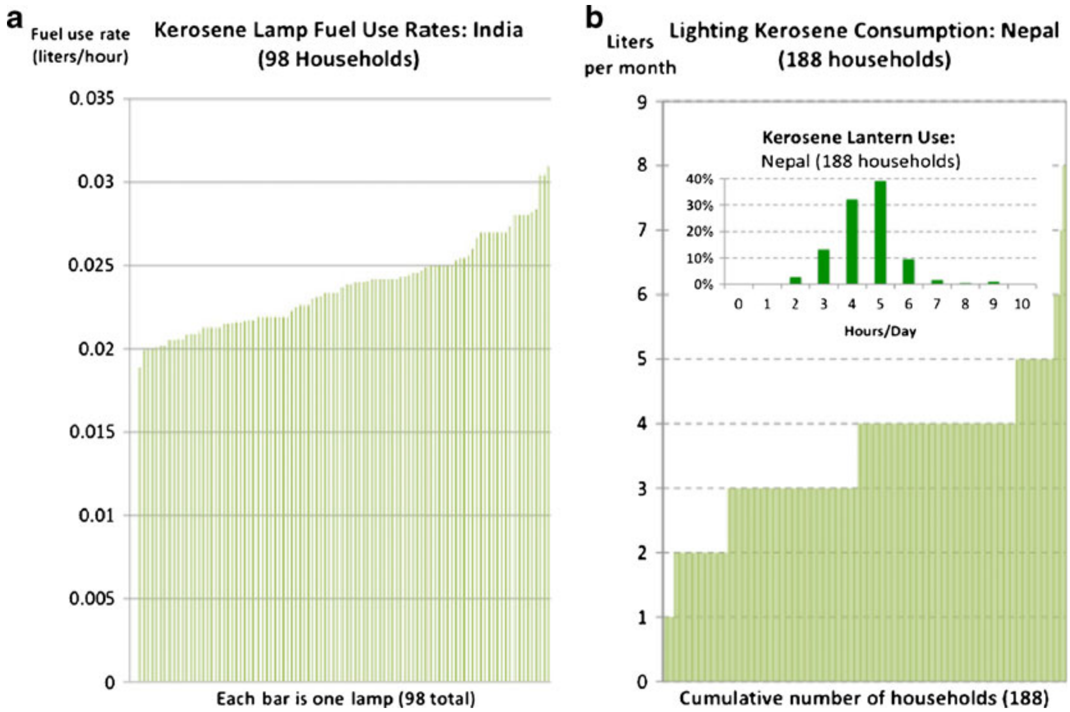


Fig. 4 a–b Distribution of kerosene lamp fuel consumption rates in Karnataka (*left*) (CDM 2009). Distribution of monthly kerosene lantern fuel consumption (*right*) and daily hours of use (*inset*), inferred from liters-per-month data, assuming average consumption rate of 0.030 l/h. Figure 4b data furnished via personal communication by Stewart Craine, Barefoot Power

uncertainty as to the service life of grid-connected compact fluorescent lamps in prior CDM efforts (Michaelowa et al. 2009).

- The cost of ownership (including initial cost and operating costs over time) of LED lighting systems can be lower than the cost of fuel-based lighting.

Off-grid LED lighting systems can also offer highly compelling non-energy benefits, including superior light quality, improved fire safety, elimination of adverse indoor air pollutants, and promotion of good conditions for studying and learning.[9]

The time is ripe for accelerating the market for improved off-grid lighting technologies in developing countries. Arguably, these markets will be receptive to LEDs well before those in industrialized countries. The baseline technology (fuel) cost is higher and their performance requirements (level and extent of lighting) are lower. Several major public–private initiatives have been established to pursue this goal. They include the World Bank Group's Lighting Africa[10] program and the US Department of Energy's Solar and LED Access Program, which are collaborating, as well as the Lighting a Billion Lives initiative and the Asian Development Bank's Energy for All initiative.[11]

While the deployment of quality assured off-grid lighting systems and significantly larger solar home systems (SHS) both represent decentralized pathways for achieving modest greenhouse gas emissions reductions, there are good reasons to believe that stand-alone LED systems have greater near-term potential to deliver reliable and affordable results for illumination. (Of course, where other energy services are required, SHS can be the preferred approach.) First, the initial cost of small, LED-based off-grid lighting systems, which are now available at retail

[9] One study claims that average study time of students rose from 1.47 to 2.71 h/day, with a positive effect on school performance (Agoramoorthy and Hsu 2009).

[10] See http://www.lightingafrica.org/.

[11] See http://energy.gov/news2009/8391.htm, http://labl.teriin.org/, and http://www.adb.org/Clean-Energy/energyforall-initiative.asp.

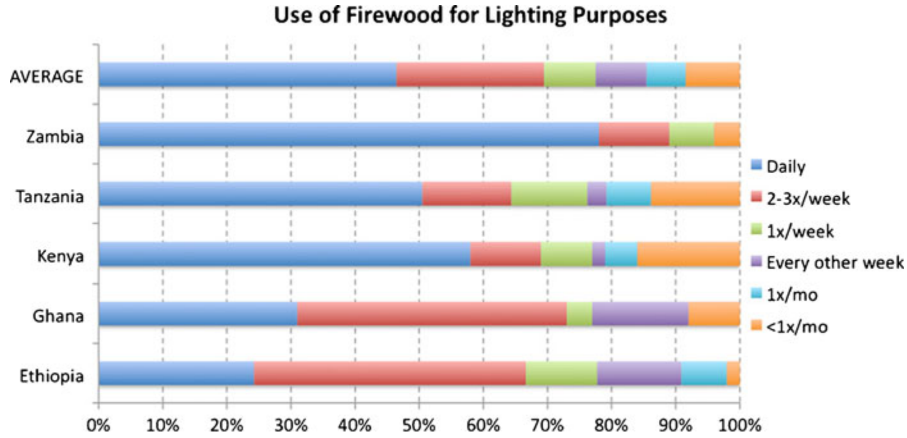


Fig. 5 Use of firewood for lighting purposes (Lighting Africa 2009)

prices on the order of $10–70,[12] are frequently five to 20 times lower than conventional solar home systems, which often sell for $300–1,000. This was born out in a recent side-by-side demonstration of LED lighting versus traditional solar fluorescent lighting in chicken production (Tracy and Mills 2010a). The lower cost of LED lighting systems makes them more broadly affordable to the lowest-income families and businesses that do not have direct access to grid power. This suggests much greater potential for widespread deployment that, in turn, could lead to greater displacement of fuel-based lighting and associated carbon emissions. Second, while LED lighting systems are designed primarily to provide off-grid lighting (and, in some cases, mobile phone charging), the energy generated from SHS can be used in many ways (e.g., for powering televisions) that often take priority over lighting (e.g., see Jacobson 2007). Third, although quality assured versions of both system types can perform well, small LED lighting systems tend to be simpler and, by extension, easier to install, maintain, and use. This simplicity can be an important factor for enabling widespread adoption and maximizing service life (Jacobson et al. 2000; Nieuwenhout et al. 2000).

While LED lighting solutions have emerged as a viable "disruptive technology" alternative, serious issues of product quality and durability are impeding the development of potentially immense markets for alternatives. There is considerable wishful and well-intended anticipation of the environmental and social benefits that may be captured from the widespread use of LED lighting systems. However, most claims gloss over important practical realities that stand to erode this assumed potential. Many claims do not expressly address the means for maximizing savings and minimizing the risks of under-attainment. There are a variety of specific performance and quality issues related to the LED light sources, optics, driver circuits, batteries, and charging systems, as well as the ruggedness of the switches and housings (Mills and Jacobson 2008; Tracy et al. 2009).

Most current commodity LED systems are low-price/low-quality products (Mills and Jacobson 2008; Johnstone et al. 2009; Mink et al. 2010). Market surveys have shown that end-users are satisfied with *some* current products, although the fit is not to be taken for granted (Mills and Jacobson 2007; Lighting Africa 2009, 2011; Tracy et al. 2009, 2010b). Surveys of early adopters in Kenya showed that 87% of LED flashlight buyers had problems within 6 months (Tracy et al. 2009). A market trial conducted in 2008 found that many of the lamps had failed by the time of a return visit 2 years later (Tracy et al. 2010a). Fortunately, private companies are beginning to offer superior choices.

Under the most disadvantageous conditions, few if any carbon savings can be expected to result from low performance LED products, while in well-designed applications the value of the carbon reductions up to approximately US $15 in our analysis represents a substantial fraction of cost of the product itself. Although baseline fuel-based lighting assumptions (e.g., hours of use) are important, far larger uncertainties exist in the attributes and viability of the replacement LED technologies, their patterns of use, and particularly their useful service life. For example, products with low-quality construction can corrode or prematurely fail in any number of other ways. Battery

[12] See http://light.lbl.gov/products.html.

technology choice also influences life in cases where batteries are not easily replaceable.[13] In some cases, products are intentionally designed for a short life, such as counterfeited “hand-cranked” lights with non-rechargeable batteries. Inability to replace batteries, emissions associated with grid charging, multifunction uses that do not offset carbon, and other factors can also de-rate the nominally assumed greenhouse gas emissions savings.

This discussion highlights the important relationship between product quality and emissions reductions potential for LED-based off-grid lighting systems. In fact, we find that systems for quantifying and valuing greenhouse gas savings from alternatives to fuel-based lighting would do well to focus primarily on the attributes of the *replacement* technologies (rather than the fuel-based baseline technology). Moreover, by incorporating product quality into the determination of emissions valuation, the dual objectives of persistent savings and fostering technology innovation are productively reinforced.[14]

Evaluation of replacement technologies should thus be an integral component of a new carbon accounting framework. In the next section, we discuss existing carbon accounting frameworks and propose an alternative that is based on deemed values that consider the attributes of the replacement technologies.

Adequacy of existing carbon accounting frameworks

The apparent simplicity of flame-based light sources and the compelling nature of the alternatives make the derivation of carbon savings seem straightforward. The temptation is to stipulate the savings as the difference between a baseline that is simply the product of an assumed fixed rate of fuel and a fixed level of use. This value is then compared to an assumption of zero emissions for a replacement electric light that has an assumed (frequently optimistic) product service life. Finally, the calculation naively assumes full substitution wherein each hour of electric light corresponds to 1 h of displaced fuel-based lighting.

This highly simplified approach might be summarized as shown in the following example:

$$\begin{aligned}
\text{Baseline} &= 0.025\ \text{l/h} \times 4\text{h/day} \times 365\ \text{days/y} \times 10\ \text{years (life)} \\
&= 365\ \text{l of kerosene} \\
\text{Energy saved} &= 365\ \text{l of kerosene (100\% offset)} \\
\text{Emissions reduction} &= 0.876\ \text{metric tonnes CO}_2\ \text{over the replacement product's} \\
&\quad \text{lifetime (assuming a 100\% kerosene} - \text{fuel baseline, and 2.4 kg CO2/liter of kerosene)}
\end{aligned}$$

As we show below, this method for estimating savings defines an unreasonably optimistic upper limit on emissions reduction rather than an expected value.

Within the Clean Development Mechanism, until recently the approved methodology known as “AMS-I.A. Electricity generation by the user” (UNFCCC 2010) has been applied to several projects.[15] Some believe this was not an appropriate methodology. In any event, it has been used and approved repeatedly.

Following are some aspects of the methodology that could be improved:

- The language is highly technical in places (including complicated mathematical formulas), which could create a deterrent to its use.
- Because the methodology attempts to cover to a very wide range of technologies and end-use

[13] Cautious estimates might be 6–9 months for sealed lead–acid batteries, 2 years for nickel–metal hydride, and 3 years for lithium ion technology.

[14] Incorporation of quality assurance into carbon emission reduction schemes could be achieved through collaboration with emerging quality assurance efforts such as that under development by the World Bank Group’s Lighting Africa initiative (http://www.lightingafrica.org/node/78).

[15] Methodology AMS II.C. ”Demand-side energy efficiency activities for specific technologies” may be applicable for grid-recharged products with battery storage.

contexts, many passages are not applicable to off-grid lighting and thus impede the method's use and precision.

- The methodology treats the baseline technology as having a highly predictable set of uniform attributes, when in fact there may be many types of sources with varying characteristics that affect the amount of greenhouse gas emission offsets.
- The methodology focuses on the household sector. Non-household users (such as night market vendors, cottage industry, schools, clinics, and fishermen) are significant and should be accommodated. Often, a single light is moved between both locations.
- The potential for increases in future emissions in the baseline is not addressed.
- The methodology calls for measurement and verification that could be too cumbersome for project developers and in cases not possible (Michaelowa et al. 2009).
- Section 7(c) Option 3 recommends a default daily usage value of 3.5 h, which is appears to be overly cautious, at least in sub-Saharan Africa.[16] This is particularly true for certain cottage industry uses, such as poultry production, which are closer to 12 h/day (Tracy and Mills 2010b).
- LED systems introduced under a given program may be characterized uniformly, even if there is a material difference in the mix of specific products deployed under the program.
- Quality assurance of the replacement lamps is relegated to the post-deployment period, but it could be more effective if done before deployment.
- The methodology is silent on product service life and has accepted dubiously long default values proposed by project developers.
- The method does not accommodate the prevalent baseline case of electrified consumers that rely on fuel-based lighting during power outages.
- The case of centralized grid-charged replacement lights is not addressed. This is a significant limitation as grid-based charging is sometimes the preferred strategy in locations where there is sufficient infrastructure (typically in the form of distributed mobile phone charging microenterprises). Thus, this provision inadvertently discriminates against one of the more popular technology options among end-users. Moreover, this grid charging bears a carbon footprint that should be accounted for (Fig. 6).
- The method implicitly assumes perfect (100%) substitution of the electric light source for the fuel used in the baseline.

When the aforementioned factors are regarded in a highly favorable manner—or disregarded altogether—projects will, not surprisingly be assumed to attain larger levels of carbon reductions than may be defensible. On the other hand, some legitimate technology options or use cases are not accommodated in the current method. Silence on key factors also invites widely varying estimates of impacts. In evidence of this, the two approved CDM projects for off-grid lighting differ by a factor of four in their stipulated per-lamp savings (from 0.31 to 1.17 metric tons CO_2 per lamp over the project life), while there is no obvious difference in the target markets or deployment strategy that would explain such a large variance (UNFCCC 2006, 2009).

The Small Scale Working Group of the CDM Executive Board (SSC WG) has been mandated to improve the methodologies for small-scale, end-user energy-efficiency projects. At its twenty-first meeting, the SSC WG placed priority on improved methodologies for estimating displacement of fuel-based lighting with efficient lighting technologies. An express goal was to reduce "the transaction cost related to monitoring aspects and to establish baseline emissions at the same time as maintaining the environmental integrity of the methodology." Thus, the twofold goals are on the one hand increased simplicity with a cautious approach to estimating emissions reductions.

Toward a viable methodology for assessing CO_2 reductions from integral off-grid lighting alternatives

Identifying a widely applicable methodology is important given the large but diffuse target popula-

[16] This is the current CDM default value, which is a low value based on recent survey results from five sub-Saharan African countries from the Lighting Africa (2009) market research. This survey encompassed 5,000 end-users across five countries. Evening use alone averaged 3.5 h/day in Ethiopia, Zambia, Kenya, and Tanzania, and 4 h/day in Ghana. Additional use in the early mornings was not quantified, but is frequently reported at 0.5–1.5 h/day, which we have observed using embedded loggers as shown in Fig. 7.

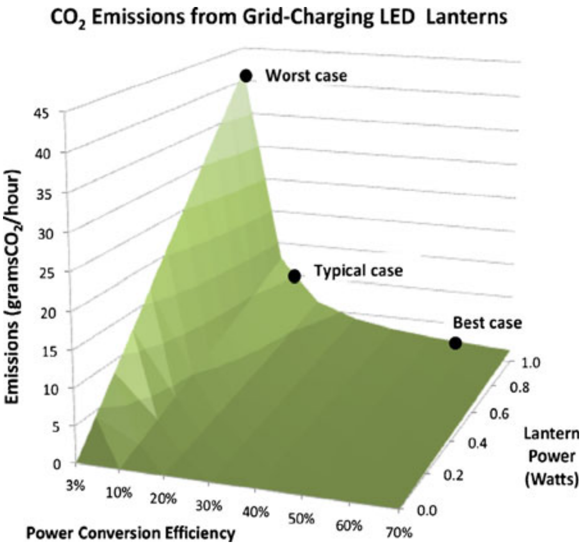


Fig. 6 Greenhouse gas emissions associated with grid-charging LED lighting systems depend on the power consumption of the system, conversion efficiencies, and emissions factors. Power supply efficiencies vary from ~3% to ~95% (Alstone et al. 2011; Ecos 2002). Minimum efficiency standards in California are 50% (California Energy Commission 2009). SLA battery efficiencies vary from 50% to 90%, depending on the charging strategy (Stevens and Corey 1996). This assessment assumes a grid-electricity emissions factor of 1,000 g/kWh (gCO_2/kWh) and 20% transmission and distribution losses. Values in developing countries range from to 600 to 1,800 (gCO_2/kWh), including transmission and distribution losses (EIA 2007). For comparison, a typical kerosene lantern results in emissions of approximately 40 g/h. In the example given, losses range from 5% to 100% of baseline lantern emissions, but losses rise steeply at the low-efficiency end of the scale. These values do not include standby power consumption that occurs when grid-connected lamps remain plugged in after the battery has been fully charged

tions, the diversity of replacement technologies, and the low potential revenues per participant compared to many other carbon-reduction technologies.

Important design principles could include:

1. The methodology is easy to understand and apply.
2. The methodology recognizes technology, user, and market drivers of outcomes.
3. Assumptions and variables can be independently verified.
4. Carbon valuation is linked to project quality and technologies employed.
5. The cost of implementation is not a barrier to its application.

We propose an improved methodology based on a cautious standardized set of basic deemed baseline and upgrade defaults that could be selected in lieu of costly field assessments. Recommended default values for the fuel-based and LED technologies are outlined and defined (Table 1), along with various factors for adjusting performance based on LED technology choices.

Alternate values should be permitted if adequate research/monitoring/documentation is provided. Interested third parties, non-governmental organizations, and governmental bodies could choose to improve the accuracy and functioning of this market by conducting strategic surveys and research to improve the basis for alternate assumptions, thereby reducing or eliminating the transaction cost of doing so faced by private businesses attempting to operate in the market. The rapid rate at which LED technologies are evolving, combined with extensive new market research yielding new information, should be considered in regular updates to the methodology.

Standardized baseline assumptions

One of the statistical benefits of small-scale projects with large numbers of participants is that a given project may be highly randomized as compared to, for example, a single large power plant. In evaluating the acceptability of variance in baseline values (Fig. 4a–b), taking the central value can accurately represent a population of lighting users or an array of lighting technologies. Recently, a new CDM methodology (AMS II J) for CFL projects pioneered the concept of including cautious default operating parameters as an alternative to costly continuous monitoring (Michaelowa et al. 2009).

While there is an overall fivefold variance in the standardized hourly rates of emissions from fuel-based lighting products as seen in Fig. 3, the vast majority of products are of the small-to-medium wick and hurricane lantern type, which vary by closer to a factor of 2–3. In practice, additional lamp-to-lamp variation is added by end-user wick management practices, wind conditions, and daily lamp use patterns. Self-reported values for these types of variables are not necessarily reliable.[17] Efforts to

[17] In a recent study (Tracy et al. 2010a), night watchmen reported an estimated time of 3.5 h of flashlight use per night; however, preliminary results from digital data logging indicates that nightly time of use is closer to 1.5 h on average. Radecsky et al. (2008) also reported higher than actual measured rates of use.

Table 1 Deemed baseline assumptions: illustrative recommendations

Baseline fuel-based lighting technology		Default value
Fuel use rate	There is a wide range of fuel-based lighting sources, and each requires its own deemed fuel-consumption baseline. For kerosene lanterns, fuel use rates range from 0.01 to 0.10 l/h with most products operating in the 0.02–0.04 l/h range (i.e., the small/medium wick lamps and larger lanterns). A value of 0.025 is a reasonable conservative approximation in lieu of superior local data	0.025 l/h[a,b]
Daily hours of use	Recent surveys of 5,000 households across five sub-Saharan countries found average lantern-use values of 3.5–5 h for evenings only (excluding early morning lighting) (Lighting Africa 2009). Irrespective of the value assumed, fixing this value without option for petitioned alternative levels would inadvertently create a disincentive for program developers to identify and target particularly high-use groups	4 h/day[a]
Days of use	For fully unelectrified users, daily use can be assumed. For unreliably electrified contexts, lower values must be used based on acceptable published information (presumably available directly from the power production authorities). For this purpose, it would be reasonable to take the average over a multi-year outage history for an appropriate region (city, sub-grid) rather than at the household level. A major challenge still would remain, however, in ascertaining whether a given buyer was using a light in a grid-connected context	365 days/year[a,c]
Fuel emissions factor	In practice, a variety of light sources may be replaced by the new technology. A context-specific blended fuel-mix could be proposed by users of the methodology. Where data are available in the open literature, UNFCCC may choose to develop official fuel mixes (emissions factors) for use as default values in specific regions or contexts. Developing appropriate emission factors for biofuels is particularly difficult. The rate given here is for kerosene	2.4 kgCO_2/l[a,b]
Suppressed-demand multiplier	The CDM does not formally permit adjustments for suppressed demand	1.00[a]
Annual dynamic baseline multiplier	A number of factors can be expected to alter baseline consumption of lighting fuels upward or downward during the service life of carbon-reducing products. These include fuel-price increases/decreases and the effects of subsidies and taxes, numbers of people per household, income, and electrification rates. If there is a basis for estimating these factors among the user population, the value can be specified as a net annual rate. At a minimum, in cases where there is increasing income, the consumption of lighting fuels will likely increase, and thus the baseline would grow during the time the alternative lamp was in service. A study of Ethiopian households estimated that kerosene use grows considerably faster than income (Mulugeta 2004)	10% per year[a]
LED replacement technology		
Leakage factor	In practice, some proportion of users will move their original fuel-based light to a different location or to use it in conjunction with the new light source. A cautious default substitution efficacy of 50% may be applied (Tracy 2010a). It could be argued that this relocated fuel-based light source is just reducing suppressed demand, and that no carbon penalty should be assessed, however no literal carbon reductions will occur in this event	50% fuel use reduction[a]
Number of fuel-based lamps replaced per LED	Well-designed LEDs may be able to replace multiple fuel-based lamps in some instances, thereby increasing the carbon offset considerably. A cautious average default assumption of 1:1 should be assumed in lieu of acceptable alternate data from the applicant	1[a]
LED service life	All electric lighting products experience a reduction in light output over time, a process known as lumen depreciation. The rate of decrease varies widely by type of lamp and quality. The Alliance for Solid State Illumination Systems and Technologies (ASSIST) recommends defining the useful lifetime for LEDs as the time at which initial light output has declined by 30%, which would be approximately 2,500 h for a fully-powered high-quality 5 mm component. At 4 h/day of operation (fully driven), this is about 2 years. The service life of larger "High-power" LEDs is on the order of 10–20 times this number (USDOE 2006). Given many other factors that can shorten product life, a more cautious assumption of seven years for products with high-power LEDs would be appropriate, given that other components of the product are likely to fail within that time, effectively terminating the product's service life	2 years[a]

Table 1 (continued)

Baseline fuel-based lighting technology		Default value
Net-to-Gross value (NTG)	NTG is a value ≤1, which represents the ratio of products obtained through the program to the total obtained in or out of the program. Because LED systems organically entering the target markets are of very limited use (virtually all flashlights) and of such exceptionally low quality that they garner negligible, if any, carbon reductions, a NTG of 1.00 can safely be assumed in the near term	1.00[a,d]
Deemed lifetime emissions (tons CO_2 over lamp life)	Product of all preceding factors in this table, with the exception of grid-charging, applied instead in Table 2	0.106 tons CO_2 (lifetime)

[a] Alternative value can be used with qualifying data, or stipulated by program evaluators

[b] Separate fuel and carbon-accounting methods must be employed for other baseline fuels, including biomass, candles, and diesel

[c] A lower value should be used for grid-connected customers using fuel-based lighting during power outages

[d] With time, or in specific contexts, the use of default Net-to-Gross (NTG) values <1.0 will become appropriate. While LED systems are currently entering the market, few if any are of the quality that would be promoted in CDM programs using this methodology

accurately measure these variables at the end-user level in a way that is cost-effective for an isolated CDM project, especially with repeated measurements over time, are likely to be futile.

Deemed-savings via standardized replacement technology assumptions

As indicated above, we recommend choosing a cautious set of default assumptions for LED replacement technologies, and then applying performance-adjustment factors to reflect varying attributes that can determine the amounts of fuel-based lighting that are ultimately offset. We note that shifting the analysis to the replacement technology addresses a number of uncertainties overlooked in the AMS-1.A methodology, and does so by applying readily available data that do not involve costly and fallible house-by-house measurement and verification processes. In this case, verification can be performed at the point of sale or even further upstream in the product manufacture/delivery process. Importantly, this approach also incorporates incentives for improving the technology and program delivery (which are absent from the current methodology).

Performance adjustments

The deemed-savings approach must be performed in the context of various uncertainties that are difficult (or costly) to measure or otherwise manage. Aside from these factors are a set of technology factors associated with the replacement systems that collectively introduce far greater uncertainty, yet, fortunately, are easier to quantify and incorporate into an assessment of real-world energy savings and carbon offsets.

These include factors influencing the product's service life, performance, and level of offsets, and product quality and reliability variables that determine user acceptance and the level of utilization.

The concepts of increases in future baseline emissions, additionality, and leakage require deeper consideration and—in some cases—adjustments to the deemed default values. These issues will be considered in the sections that follow.

Increases in future baseline emissions during the project period

As an energy end-use, lighting has unique characteristics and complexities compared to many other energy services. Lighting users' needs vary widely, from small incidental applications to higher intensity and continuous ones. The quality and quantity of acceptable illumination also vary. For some, tasks color rendition or glare are not important; while for others, they are critical.

The level of lighting service provided by fuel-based lighting is very small; light levels from fuel-based lamps are commonly 1–5% of those called for in illumination standards in industrialized countries (Mills and Borg 1999; Mills and Jacobson 2007). For example, the Western standards for light levels ("illuminance") can vary from 100 to 10,000 lx (lumens/square meter) depending on the activity being illuminated. In contrast, a kerosene lantern may deliver only 1–10 lx. There is no consensus as to the minimum acceptable illuminance levels or light output from qualified LED systems.

As can be seen from Fig. 1, there is massive pent-up demand for lighting services in the developing world: a quarter of the world's population consumes far less than 1% of the utilized illumination services. Moreover, users of fuel-based lighting obtain less than a thousandth of the illumination energy services per unit of money spent on illumination as do those in industrialized countries. The poorest of the poor thus pay far more than the rich for each unit of illumination.

Consumers surveyed in sub-Saharan Africa report two to three rooms kept dark in the evenings, while both consumers and off-grid businesses report inadequate illumination and rank improved lighting highest among a set of improvements desired for their premises (Lighting Africa 2011). Conversely, a project in Malawi found that lighting use increased from 2.7 to 4.4 h/day (63%) after the introduction of LED systems (Adkins et al. 2010). Household surveys conducted under a CDM project based in Karnataka, India, found that existing households had one to three lamps and would acquire an additional four lamps if they could afford the initial cost and operating fuel (CDM 2009). They estimated that actual kerosene consumption was about one seventh of what it would be if they could afford to operate more lamps for more hours each day.

While it may not be appropriate to explicitly account for these factors in the determination of greenhouse gas emissions reductions, they must be considered in the selection of replacement technologies and the design of deployment programs in order to maximize the chances for customer acceptance, retention, and persistence of the change.

On a lamp-for-lamp basis, a high-quality LED lighting system designed for developing country applications can produce illumination levels for task lighting that are 10–100 times higher than those produced by the baseline flame-based lanterns. If users then aspired to extend that higher lighting level throughout their homes or businesses, the implied increases in future baseline emissions during the course of the project grows again many-fold. The amount of lighting fuel required to replicate this expanded level of service would amount to many thousands of times of current usage. However, equating all of this phantom fuel offset by LED lighting systems would result in hundreds of dollars of notional carbon value for each lantern—tens of times the total price of that lantern—severely distorting the market while crediting imaginary carbon savings.

A potentially more defensible treatment for increases in future baseline emissions (because it could plausibly change/manifest during the project period) would be to consider and quantify two factors:

1. Rising emissions due to technical as opposed to economic factors. These would include temporarily curtailed use of the baseline lantern due to restricted kerosene availability (rather than insufficient income to purchase).
2. Growth in the fuel-based lighting baseline in the absence of the LED alternative over the proposed project period, with growth indexed to increased incomes as well as kerosene price effects that could boost (or shrink) demand for kerosene. Geographically based indices for kerosene prices could be based on price elasticities from the literature or on field research conducted expressly to determine the relationship. Linking corrections to these historical socioeconomic factors would also be a more quantitatively rigorous approach insofar as the time horizon for growth in illumination consumption is not practically measurable.

In thinking about the dynamics of lighting choices over time, it should be noted that households and businesses using fuel-based lighting tend to purchase more expensive lamps that generate more light at a higher rate of efficiency (but with higher absolute rates of fuel use) if and when their purchasing power increases (either through increased income or decreased prices). For example, a user could upgrade from a wick to kerosene to pressurized lantern, while increasing the number of lanterns and hours of use. The upper limit is the point at which the user is well enough off to switch to grid-based electricity, and thus represents an absolute cap on the potential increases in future baseline emissions during the course of the project.

The briefer the project period, the lower the expected effect either of these factors. Both factors would also be difficult to quantify in practice, and for this reason it may not be practical to produce defensible estimates.

Additionality

Lighting systems based on white LEDs are only just beginning to penetrate markets in the developing world. The question appropriately arises as to whether savings from programs under the CDM would yield net benefits compared to business as usual and thereby meet the requirement of "additionality". The term "net-to-gross" savings is also used to describe this effect.

The cost of LED systems represents an established market barrier to natural adoption, particularly for the lowest-income target audiences. By effectively increasing the payback time by many-fold, fuel price subsidies (particularly high in India[18] and Indonesia) create a significant barrier to the uptake of new lighting technologies. Import duties magnify this departure from true–cost relationships among consumer choices. Taken together, these factors amplify intrinsic economic barriers by depressing the cost of the polluting baseline and magnifying the relative cost of the alternatives.

The prices of LED technologies being offered to developing countries vary widely. Commodity, low-quality products (generally in the form of flashlights) are typically priced at under \$5. Higher-quality, higher-performance products fall in the \$10–50 range (some much higher, which is not realistic for the lowest-income markets). Recent market research has estimated end-user willingness to pay for such products (Fig. 7). While there may be some exceptions, it appears that current retail prices often exceed the willingness to pay, suggesting a role for incentives such as those that may be generated through CDM projects. However, this relationship could change dramatically in the future as LEDs become less expensive. In any event, the availability of carbon-credit incentives should not be allowed to bias manufacturers against seeking lower cost production methods.

There are several other modes by which LED projects under the CDM can be expected to achieve additionality. The first is by accelerating market penetration. While LEDs have become common in battery-powered flashlights (Johnstone et al. 2009), they are virtually non-existent in other lighting contexts in which fuels are the baseline energy source. The extreme income sensitivity of the target audiences and the relatively high first cost compared to incumbent baseline technologies (which could be higher by 100-fold, e.g., \$0.20 versus \$20.00) suggests that baseline "unaided" market penetration may be quite slow. However, as LED prices fall they may cross a point at which demand is large without the benefit of carbon valuation. A recent study found that the uptake rate of LED alternatives was very sensitive to income (Adkins et al. 2010).

The second and more important argument for additionality has to do with product quality. The current trend is toward very low-quality LED products, which are spoiling the market and thus slowing demand (Mills and Jacobson 2007; Tracy et al. 2009, 2011). In lieu of interventions aimed at restoring quality and end-user trust in this technology category, penetration will be very low and cumulative savings will be diminished due to the minimal service lives achieved before products fail. Conversely, products and programs that embed high quality standards will secure durable emissions that are strongly additional to those in the business-as-usual scenario.

A third factor that argues for significant additionality in CDM-based off-grid lighting programs is the absence of adequate market conditions to enable improved off-grid lighting technologies to gain a foothold. Programs enabled through CDM could potentially create or improve local institutions, support financing mechanisms to overcome first-cost sensitivities, mount information and education campaigns to better equip sellers and buyers to engage, and create or improve supply chains for critical components (e.g., replacement batteries). Doing so can clearly accelerate market uptake (Adkins et al. 2010). Companies developing off-grid lighting products can have difficulty accessing investment capital. Securing carbon payments is one way to reduce perceived risk by investors.

Another criterion for additionality—that improved products not be required by law—is clearly met in most cases. There will be exceptions and the CDM

[18] Households targeted by a CDM project in Karnataka were said to pay as little as 12 Rupees/l (\$0.25/l) for kerosene (CDM 2009), which is substantially lower than prices of \$1–2/l observed in sub-Saharan Africa.

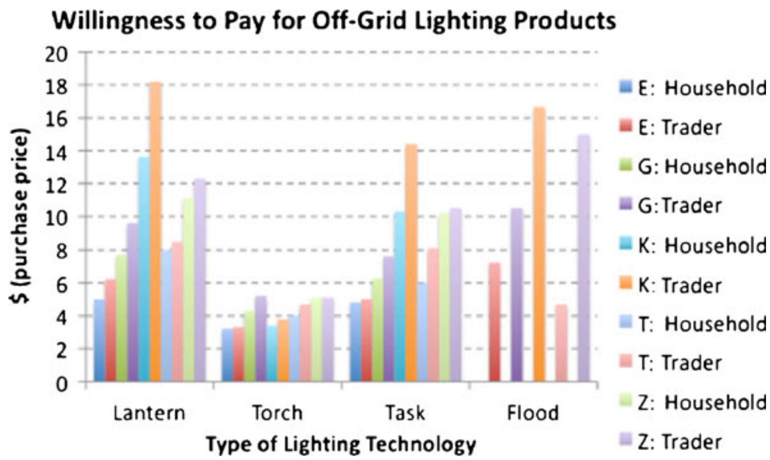


Fig. 7 The willingness of households and traders to pay for rechargeable off-grid LED lighting systems varies by country, user type, and type of lighting service provided. Countries: Ethiopia (9.95 ETB/US$), Ghana (1 GHC/US$), Kenya (66 Ksh/US$), Tanzania (1,181 Tsh/US$), and Zambia (3,333.3 ZK/US$). Source: Lighting Africa (2009)

should monitor this for use in evaluating prospective projects. For example, in late 2009, Peru outlawed the use of kerosene for lighting and cooking.[19] They are promoting integrated off-grid electric lighting in its place, probably through product give-away programs (Centeno et al. 2009).

One contingency to be considered is a program recipient's home or business eventually becoming electrified. A grid-based incandescent lamp is responsible for about 10–100 g of CO_2 emissions per hour,[20] which is the same order of magnitude as the emissions rates kerosene lanterns depicted in Fig. 3 (but the electric lamp of course generates vastly more light). If off-grid LED systems cease being used when an entire home becomes electrified, then there may no longer be carbon savings. On the other hand, decommissioned LED systems would, in practice, be placed into use by others (even in the same family) who remained off the grid. Moreover, the presence of the LED systems, especially where other modest functions were served (e.g., television and cell phone charging) could defer for a period of time a consumer's move to the grid.

If current trends in technology development (lower cost, higher performance components) and policy efforts are successful, the role for CDM in off-grid lighting will be limited to the near term. Important differentiators of LED product lifetime notwithstanding, LED lighting systems are generally much shorter-lived products, which entail less speculation and need for long-term monitoring to ensure that deemed lifetime performance is maintained in practice. Moreover, high-quality LED systems are generally designed to be nearly maintenance free (the primary maintenance is an occasional battery change), thereby reducing uncertainties about durability. In contrast, many other types of CDM projects claim emissions that are based on very long asset lives (e.g., 20–30 years), which of course increase uncertainties about the full lifetime emissions being attained.

Taken together, the aforementioned factors suggest that, given their current miniscule market penetration due to a combination of economic and institutional factors, integrated LED lighting systems are far less susceptible to additionality concerns in the near term than many more well-established technologies currently deployed within carbon markets. Given the short product innovation lifecycle, baseline conditions, and methodology assumptions can be revised regularly with little risk of inappropriately grandfathering legacy projects. That said, the technologies, their costs, and other market factors are changing rapidly. It would be prudent to revisit the issue of additionality regularly and to make adjustments to this aspect of the methodology as necessary. CDM's applicability in a given country or region could even be benchmarked to a specific rate of market penetration for quality products, e.g., 20%.

[19] In legal rule D. S. No. 045-2009-EM on 29 April 2009, the Peruvian government banned the sale of kerosene nationwide.

[20] This range is defined depending on lamp type and grid carbon emissions factors. A 100-W incandescent lamp and an emissions factor of 1,000 g CO_2/kWh of electricity would correspond to about 100 g CO_2/h, a 15-W compact fluorescent lamp and an emissions factor of 500 g CO_2/kWh of electricity would correspond to emissions of 8 g CO_2/h.

Leakage

Leakage is defined as the net change of anthropogenic emissions by sources of greenhouse gasses which occur outside the project boundary, and which are measurable and attributable to the CDM project activity (3/CMP.1, Annex, paragraph 51). This problem would arise in the case of fuel-based lighting if, for example, the fuel-based lantern displaced by the LED light was transferred out of the project boundary.

Alternatively, some fuel-based lanterns are likely to remain in use within the project area to illuminate a previously dark area. A recent study (short-term, self-reported data) found more than an 80% kerosene reduction—and an even higher rate for candles—across 54 homes in Malawi (Adkins et al. 2010). Observations in Kenya found approximately 50% reduction in expected savings for night traders (Alstone et al., in press) and 14% for households (Tracy et al. 2010a).

There is a strong likelihood that baseline lamps will be kept in use to some degree. We suggest a provisional 50% "leakage factor" assumption default. A lower factor could be allowed based on additional research or if the project developer implements a persuasive means of reducing this risk. Smaller factors could be applied for user certain groups that are unlikely to continue using their kerosene lanterns (e.g., poultry producers using lights to extend the eating period for their birds, per Tracy and Mills (2010)). Given their very low cost (e.g., $0.20 for a standard wick lamp), destroying the baseline lamp is unlikely to be beneficial, given that these lamps are easily remanufactured at an extremely low cost.

Monitoring

AMS-1.A (Section 14) calls for monitoring in the form of "[a]n annual check of all systems or a sample thereof to ensure that they are still operating (other evidence of continuing operation, such as on-going rental/lease payments could be a substitute)." Such monitoring is highly onerous and cannot, in most cases, be expected to be cost-effective for distributed energy projects such as off-grid lighting deployment. This condition serves to discourage the development of projects, which limits the CDM to larger scale efforts.

Our proposed framework provides a more pragmatic alternative in the form of a very short deemed service-life proxy (2 years) and other deemed performance defaults. Projects that opt to institute monitoring can benefit by being assigned a longer service life, provided that their product demonstrably lasts beyond the default service life. Note that many other factors also affect service life and are taken into account in the framework.

Longer service lives could be assumed in the case of ongoing rental/lease payments, as provided in the existing methodology. Warranty or insurance-backed products could also be allowable mechanisms for deeming longer service lives.

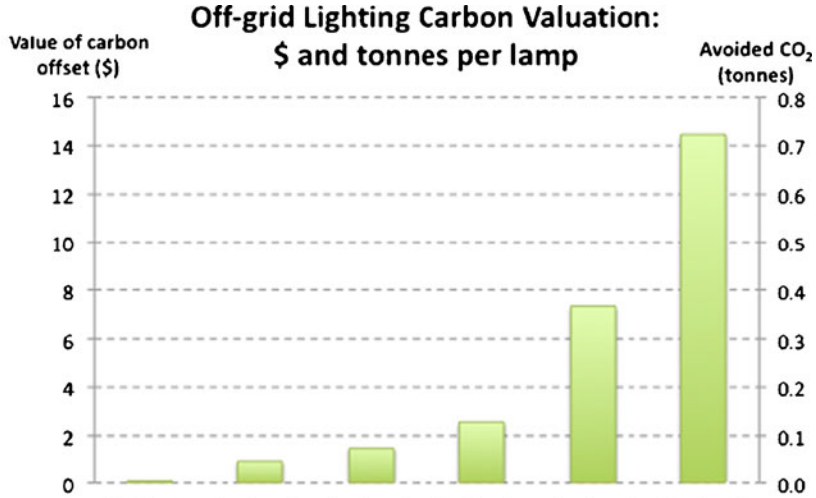
Market factors

A variety of "soft" factors also influence project success. Perhaps the most fundamental of these is consumer acceptance. Many lighting users are highly discriminating in their preferences and willingness to pay (Mills and Jacobson 2007). This is not surprising, given the high proportion of income spent on lighting, very specific expectations on product performance, the front-loaded cost of the replacement technologies, and the widespread existence of low-quality electronics in most developing country marketplaces.

Related factors include the quality of the market infrastructure in which the products are nested, such as an adequate variety and availability of products, financing, and the efficacy of product sellers in helping users match the right light to their needs. After-sales service and a viable supply chain for replacement parts and warranty are also important. For grid-charged devices, the availability, reliability, and affordability of charging services are crucial.

For well-manufactured products, the component with the shortest service life will commonly be the battery. Thus, availability of matching replacement batteries (and users' ability to open the product in order to easily replace them) is important to ensure that products remain in service for their expected period of time. Both currently approved CDM projects include at least one product with a battery that is soldered into the light, drastically reducing the respective lights' service lives to on the order of 2–3 years. Those projects, however, assume service lives of 5 and 10 years.

The relative product prices and availability of alternatives will create an elasticity effect on demand, with higher prices and/or limited choice leading to



	Product A	Product B	Product C	Product D	Product E	Product F
Baseline fuel	battery	kerosene	kerosene	kerosene	kerosene	kerosene
Type of LED	5mm	5mm	5mm	high-power	high-power	high-power
Replaceable battery	no	yes	no	no	yes	yes
Warranty	no	yes	no	yes	yes	yes
Multifunction	no	yes	no	no	yes	no
Charging strategy	grid-only	grid-only	solar+grid	solar	solar	solar
Truth-in-advertising	no	no	yes	yes	no	yes
Certification	none	Level-1	Level-2	Level-3	Level-2	Level-3

Fig. 8 Based on hypothetical inputs for the proposed system, the value of emissions varies widely depending on product attributes. Assumes carbon price is \$20/ton of CO_2. Values shown are summed over the life of the lamp. All products offset the same baseline scenario. See Table 2 for definitions of product characteristics

reduced uptake of the new technology. Conversely, delivery mechanisms (such as charity models) that circumvent traditional market processes may result in mistreatment of products and attenuated service life (and thus reduced cumulative emissions reductions).

Risk management and financing

Risk management can occur at various points in the value chain. The effort should begin at the point of manufacture. An in-house quality control, quality assurance system is critical, and should be augmented by independent rating and labeling. Factories manufacturing qualifying projects could be subject to CDM field inspections.

In carbon markets, insurance products are emerging to manage non-delivery risks. Examples include Munich Re's (2007) Kyoto Multi-risk product. Insurance and warranty projects for the underlying technologies can also be appropriate, especially when proactively based on an engineering-based assessment of product quality.[21] A number of insurers offer renewable-energy performance or energy savings insurance instruments (Mills 2003, 2009). Products have not been fashioned expressly for small-scale CDM projects, but may be in the future.

Micro-insurance is already used by nearly 80 million people globally (Mills 2009), and micro-finance by an even larger population. Application of these financial services to small-scale carbon abatement technologies is a natural extension. In this context, carbon-performance insurance for off-grid LED projects would represent an interesting market mechanism for managing risks of the attainment of emissions. Insurers would be compelled to conduct their own due diligence of products and projects, which would introduce an additional layer (albeit unconventional) of quality assurance that could achieve some of the same objectives as conventional project monitoring. Claims "paid" with equivalent CERs could be of additional interest.

Hypothetical application of the proposed framework

In the proposed framework, default values would be stipulated, and only over-ridden if acceptable data were provided. Research and surveys by neutral parties could be periodically reviewed so as to improve the deemed default values or make them

[21] See http://www.insurance4renewables.com/

Table 2 Adjusted-performance carbon valuation

		Default Value	Product A	Product B	Product C	Product D	Product E	Product F
Technology modifiers								
LED Technology service life	User of 5 mm technology can petition for extended life if acceptable documentation of under-driving the lights (to extend life) is provided. High-power LEDs assumed 7-year life	2.0	2.0	2.0	2.0	7.0	7.0	7.0
Rechargeable batteries	Rechargeable batteries have a limited life, which varies by the technology. Good-quality nickel-metal-hydride batteries can be expected to last perhaps 2–3 years in practice, and less than 1 year for lead-acid batteries. If the battery compartment cannot be opened, then the battery end-of-life determines the entire product's end of life. Consumer must be able to change battery without tools; otherwise life capped at 2 years	No	No	Yes	No	No	Yes	Yes
Warranty	Absence of a warranty or other risk-guaranty product (e.g., carbon-offset insurance, or product/component performance insurance) may reflect the manufacturer or intermediary's degree of confidence in the product and the user's ability to have it repaired or replaced if it malfunctions. Absence of a warranty or insurance can form the basis of de-rating the default product lifetime, e.g., by 25% in this illustration, or excluding it altogether	No	0.75	1.00	0.75	1.00	1.00	1.00
Adjusted product service life		Calculated	1.5	2.0	1.5	2.0	7.0	7.0
Baseline lighting energy source	Default values may assume a fossil fuel as baseline, but in some cases other energy sources are used. Biofuels could have higher or lower net emissions than fossil fuels. Replacement lighting systems that primarily replace a battery-powered lighting baseline (e.g., traditional flashlights or "torches") could be expected to save very little fuel. De-rating the baseline assumption by 90%, may be appropriate to account for this. However, a flashlight form-factor is not necessarily problematic if it provides effective hybrid modes of operation including ambient light or non-handheld task lighting that end-users deem adequate for replacing fuel-based lights	Kerosene	0.10	1.00	1.00	1.00	1.00	1.00
Multifunction capability	Some innovative lighting technologies being brought to market support non-lighting functions such as cell-phone charging or radios. In this case, there is competition between uses that displace fuel and those that do not. Less than a 1:1 offset of the baseline lighting may result from reduced lighting hours from the device. This effect will be strongest in larger solar home systems (SHS) where significant non-lighting loads are being met. Savings could be de-rated by 25% to account for this effect	No	1.00	0.75	1.00	1.00	0.75	1.00
Power conversion losses (for grid charging)	Solar-powered charging savings would be regarded as "off-grid". In many areas, however, end-users prefer products that can be grid-charged, e.g., via cell-phone charging shops or other battery-charging methods. If the local grid uses fossil fuels and the charging efficiency is low, then a non-trivial amount of greenhouse gas	1.00	0.75	0.75	0.90	1.00	1.00	1.00

	emissions will be emitted (Figure 6). In this context, efficiency is based on the differential between power delivered to the AC adapter and that ultimately released by the battery to the light. A cautious default emissions rate for a product that is always grid-charged is 25% of that from a standard kerosene lantern (10% if the product is chargeable on or off the grid). High-efficiency charging yields negligible losses. Conversely, if off-grid lights are used by electrified consumers during power outages, carbon savings may result if the alternative baseline technology choice is back-up fuel-based lanterns. In either case, grid-based emissions can be calculated using the CDM methodology known as "AMSI.D"							
Quality modifiers								
Truth in advertising	Research has shown that many off-grid lighting products do not perform as advertised (Mills and Jacobson 2007). Underperforming (or counterfeit) products will disappoint the user and are not likely to remain in use as long as accurately advertised ones. Factors to be considered include battery capacity, light output, and product life. Default emissions values could be de-rated by 25% (or products disqualified) if there is evidence of failure to provide truth in advertising with regard to product characteristics or performance	0.85	0.75	0.75	1.00	1.00	0.75	1.00
Certification	An independent product quality rating (e.g., that being developed by the International Finance Corporation and the World Bank Group's Lighting Africa Project) would make it possible to differentiate among products on the basis of performance and durability, which are strong determinants of how long the product is likely to remain in service. One of many examples of factors that would not otherwise be visible to a buyer would be the durability and lifetime of the embedded LEDs, which, as discussed above, could vary from weeks to years. Assuming a multi-level rating, de-rating factors on the order of 10% could be applied for the absence of any given level							
Level-1	Derated 10% if no certification at this level	0.90	0.90					
Level-2	Derated 10% if no certification at this level	0.90	0.90	0.90				
Level-3	Derated 10% if no certification at this level	0.90	0.90	0.90	0.90		0.90	
Effective product service life	Product of individual multipliers (to be applied to baseline deemed savings from Table 1)	Calculated	0.06	0.68	1.22	2.00	3.54	7.00
Cumulative dynamic baseline multiplier		Calculated	1.15	1.21	1.15	1.21	1.95	1.95
Carbon emissions reduction over product effective service life		Tons	0.004	0.044	0.074	0.128	0.366	0.723
Market value of carbon (at US$20/ton)		Metric tonnes	0.1	0.9	1.5	2.6	7.3	14.5

more case-specific. Large research and deployment programs currently underway (Lighting Africa and the Solar and LED Access Program) are producing extensive information of this sort, as exemplified by Lighting Africa's surveys of thousands of households in Ethiopia, Ghana, Kenya, Tanzania, and Zambia (Lighting Africa 2009, 2011). For example, the majority of households in Zambia report that their flashlights and solar-powered lanterns last only 1 year or less (Lighting Africa 2009). These reports also provide information on lighting fuel mix by country (Fig. 2a–b).

One of the benefits of the proposed framework is that all of the deemed input values can be determined before the technology is deployed and without market surveys. Petitions for alternate values can be supported by market observations that do not require costly and intrusive visitations to individual users.

In evaluating the persistence of specific LED products, disclosure of product returns and repairs under warranties may provide justification for adjusting service-life assumptions.

Figure 8 provides an illustrative implementation of the proposed framework. The figure shows results for six hypothetical products, spanning a wide range of operating conditions and product quality. The examples are developed in greater detail in Table 2.

- The worst-case product receives essentially no valuation for carbon emissions reductions. This hypothetical product uses shorter-lived "5 mm" LED lights, is grid-charged, has no performance warranty, has a non-replaceable battery, substitutes for a battery-powered baseline technology (a conventional flashlight, which defers little kerosene), is a multi-function device with a built-in cell phone charger (which diverts some battery power), and bears no independent quality rating. The product's advertised claims could not be replicated with lab tests. The product receives nearly no carbon credits.
- The best-case product employs long-lived "Power LEDs", has a replaceable battery, provides a warranty, is strictly solar charged, complies with truth-in-advertising criteria, and has been certified at the highest quality assurance level by an independent testing body. This product produces substantial carbon offsets valued at about US$15 over the life of the lamp.

It should be noted that a given CDM project is likely to incorporate multiple brands and/or models of LED lighting systems, each of which may score differently in the proposed framework.

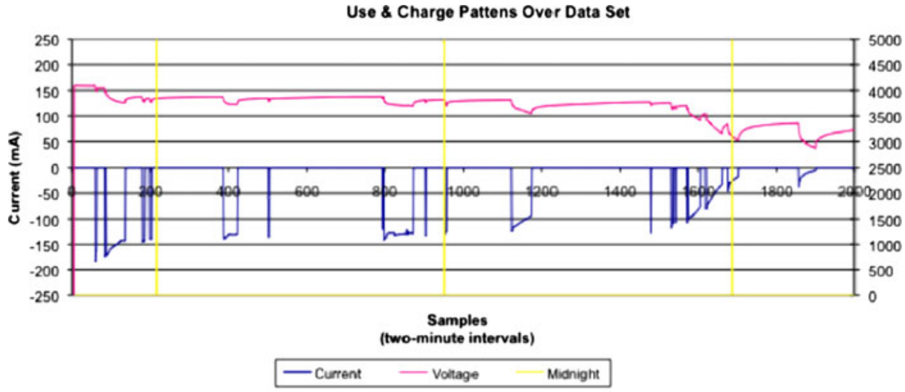
The CDM is not a panacea. There exist a variety of issues that, while not intrinsic barriers to the deployment of improved off-grid lighting technologies, confound efforts to perfect a methodology within the bounds of CDM. Examples of these are accounting for use among weakly electrified consumers who use lamps during outages, treating biomass fuels used for lighting, accounting for grid-charging of otherwise off-grid products, quantifying increases in future baseline emissions during the course of a project, defining dynamic baselines, and adjusting for the additionality concerns associated with the degree to which these technologies would be adopted in the absence of the ability to monetize the carbon reductions. Moreover, the rate of evolution of CDM protocols is not keeping pace with the rapid development of the technologies they are intended to support. Indeed, LED products have evolved even during a given project evaluation and approval process, such that technologies described in project proposals differ from those available at the time of ultimate deployment. The extremely long lead-time for approval of CDM projects (~2 years) is thus in itself a formidable barrier to the use of this mechanism.

Enabling tools and analyses

The framework offered in this article is conceptual in nature and the examples given are indicative—rather than prescriptive—for the purposes of discussion and refinement. Various sorts of research and analysis can support implementation of the recommended system and determination of actual values to be used in the framework.

Given the popularity and likely large market share of grid-charged systems, it is important to develop a better sense of the associated emissions. A key factor is to quantify the losses between grid power and energy delivered to the light. These include AC adaptors and battery chargers, batteries, and circuitry that might be in the pathway.

Independent product assessments and ratings would provide one of the most valuable streams of information for use in de-rating or enhancing the



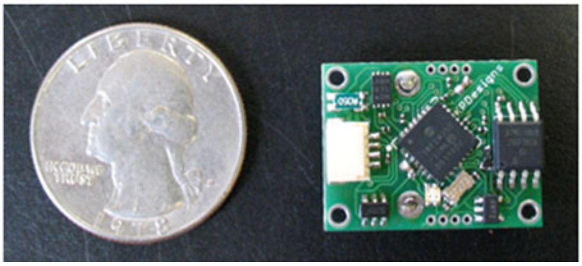


Fig. 9 Micro-logger for monitoring on-time for off-grid LED lighting products. The chart shows an excerpt of data collected for one user in Kenya over a 3-day period. For this particular trial, the average LED lamp utilization (*blue curve*) was 2.6 h/day. Note dual morning and evening use patterns. As battery loses charge on the third night, the light output can be seen to decrease. The logger was designed by Kyle Palmer and others at Humboldt State University (HSU); photo/data gathered by Peter Alstone at HSU

default offset assumptions. The Lighting Africa Project and the Renewable Energy Deployment Initiative are currently developing such systems. Encouraging more of this sort of "public goods" research would result in data independent of specific for-profit validator interests (Schapiro 2010), while alleviating considerable financial disincentives from individual companies for whom collecting such data in support of a single project would be cost-prohibitive or a conflict of interest.

Product labeling systems could prove to be a key tool for simplifying the application of the quality assessment elements of the framework proposed here. Such systems would provide an objective set of metrics in turn used as a proxy for product quality and service life. Moreover, this would enable project applicants to ensure and verify performance in advance of applying for CDM project qualification, which in turn, would result in higher quality projects, deeper and more durable carbon reductions, and enhanced additionality compared to a business-as-usual pathway that is currently introducing many suboptimal products into these markets.

Although not included in the existing CDM protocol, the embodied energy and associated greenhouse gasses of off-grid products could potentially be incorporated in the analytic framework. One investigation determined that the embodied energy of one off-grid LED product is recovered in 1–2 months of operation, a modest value that can be expected to decline over time (Alstone et al. 2011).[22]

Improved estimates of baseline global carbon emissions from off-grid lighting would help in characterizing the overall potential market. The one value in the literature (Mills 2005) should be updated and refined to include intervening demographic changes, new data and understandings about the technologies, and specific examination of biofuels in the provision of illumination. One factor that has not been previously evaluated is the perhaps significant role of "black carbon" (soot) in the overall climate-forcing impact of fuel-based lighting. The various fuel-based lighting sources all emit some amount of black carbon, but black carbon's global warming potential is not currently recognized in CDM projects.

[22] It should be noted that new LED systems with rechargeable batteries that replace conventional flashlights offset significant solid waste production in the form of non-rechargeable batteries (implying additional embodied carbon reductions). Moreover, there are carbon emissions associated with producing and distributing liquid fuels, which may alone outweigh those embodied in the manufacture of LED lighting systems.

Improved data on the utilization of baseline technologies can help refine the default values and perhaps provide different authorized datasets for different geographies or demographics. Cost-saving methods for collecting field data could provide a valuable basis for adjusting default assumptions. Low-cost light loggers have been developed and field-tested in off-grid lighting products, but not yet commercialized (Radecsky et al. 2008; Fig. 9). If non-intrusive data recovery (e.g., through short-range wireless networks) could be applied, then utilization assumptions could be validated at the project level at a lower cost (and with less self-reporting error) than if in-person interviews were required. However, safeguards would be necessary to manage risks of gaming or fraud. Independently orchestrated surveys (e.g., conducted by governmental or non-governmental organizations for public interest applications) would be less susceptible to these concerns.

Conclusions

There is massive need for improved lighting services in the developing world. Current efforts to meet those services involve the use of highly inefficient liquid and solid fuel combustion, which results in substantial greenhouse gas emissions as well as other adverse impacts such as compromised indoor air quality.

Grid-independent lighting systems based on LED light sources offer a very promising alternative for simultaneously improving lighting services and reducing greenhouse gas emissions.

Some developers of projects to promote this technology seek to monetize the carbon emissions reductions that are achieved. However, only two off-grid lighting projects under the CDM have been previously approved (CDM 2008, 2009). The lengthy project documentation and methodology proposed by project developers varies considerably; there is very little standardization. It would create greater transparency for policymakers and remove barriers for project developers if a more uniform and cost-effective methodology was implemented.

A more accurate and effective CDM methodology could eliminate the need for costly field investigations by relying instead on certain deemed baseline parameters combined with consistent adjustments based on more readily available market data and quality assessment of the incoming LED technologies. These adjustments manifest largely with respect to effective product lifetime and thus its cumulative emissions reductions, and can lead to much more internally consistent estimates of carbon savings than is the case at present with divergent methods designed by project developers.

Aside from its traditional role of directing capital from wealthy countries toward highly cost-effective carbon-reduction projects in the developing world, in the case of off-grid lighting systems the CDM, if properly applied using a framework along the lines of what is proposed in this article, can play a highly meaningful role in promoting improvements in the quality of products offered to the marketplace. The logical outcome would be significantly higher uptake and end-user satisfaction with improved lighting systems than could occur through sole reliance on existing imperfect market forces.

Epilog: A new CDM methodology for off-grid LED lighting

Based on the analysis presented in this article, the CDM has released a new approved methodology AMS-III-AR for quantifying the carbon reductions of LED lighting systems in off-grid contexts (UNFCCC 2010). The methodology incorporates much of the framework set out in this article.

The guiding principles are to provide a method more well-suited to LED projects and reducing the time and cost of qualifying a project and documenting the carbon savings, while requiring performance disclosure and embedding new criterion for minimum product quality while rewarding those products that exceed these minimums. In most cases, independent testing is required in order to demonstrate performance.

Based on the minimum performance criteria specified in the new approved methodology, the deemed savings would be appropriately modest: 0.16 tons of CO_2 per lamp (over a 2-year deemed service life). Moreover, low-quality products (or those lacking a warranty) are ineligible for any level of CERs. Conversely, alternate values for many “default” factors can be used if adequately justified by the project developer, which could bring the avoided emissions significantly higher.

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