# Economic and environmental performances of solar LED lanterns under the Clean Development Mechanism: The case of Cambodia

*De Schepper Ellen, Hasselt University, Diepenbeek, Belgium*
*Lizin Sebastien, Hasselt University, Diepenbeek, Belgium*
*Van Passel Steven, Hasselt University, Diepenbeek, Belgium*
*Durlinger Bart, Blonk Consultants, Gouda, The Netherlands*

## Abstract

The two core objectives of the Clean Development Mechanism (CDM) are cost-effective emission reduction and sustainable development. Despite their large potential to contribute to both the objectives, solar projects play a negligible role under the CDM. In this research, the greenhouse gas mitigation cost is used to evaluate the economic and environmental performances of solar LED lanterns. In particular, we compare the use of absolute and relative mitigation costs to evaluate the attractiveness of these projects under the CDM. Using a case study in Cambodia, we demonstrate that the relative mitigation cost of emission abatement over the lifecycle of solar powered LED lanterns is negative compared to kerosene lighting, meaning that the financial benefits outweigh the costs even before considering the value of reduced emissions. It is found that the reduction potential of solar LED lanterns under the applicable CDM method AMS-III.AR is well approximated. Policy recommendations are the following: *(i)* We encourage the use of relative mitigation costs, implying consideration of baseline costs that render the projects profitable. Our main suggestion is developing guidelines to create an additional revenue stream of avoided baseline costs. *(ii)* We discourage the use of absolute limits on the crediting period. Rather, we advise to deliver certified emission reduction units over the operational lifetime in order to stimulate technological development. *(iii)* We encourage the increased use of standardized baselines to avoid manipulation of the system. Inclusion of these guidelines can boost the use of solar LED lanterns under the CDM.

## Introduction

Countries committed to the Kyoto Protocol must meet greenhouse gas (GHG) emission reduction targets primarily through national measures. As an additional means of compliance, the Kyoto Protocol launched three market-based mechanisms, thereby creating the “carbon market”. These mechanisms are *(i)* Emissions Trading (ET), *(ii)* Joint Implementation (JI), and *(iii)* the Clean Development Mechanism (CDM). The ET allows countries that have spare emission units to sell this excess capacity to countries that are over their targets. The JI and CDM are both project-based mechanisms which feed the carbon market. The former enables industrialized countries to carry out joint projects with other developed countries, while the latter involves investment in sustainable development projects that reduce emissions in developing countries (UNFCCC 2014). Moreover, in the CDM, projects can earn saleable certified emission reduction (CER) credits -each equivalent to one ton of $CO_2$- that can be used towards meeting the Kyoto targets (UNFCCC 2014).

In particular, the CDM is designed to meet two objectives, namely to help Annex I parties (developed countries with specific limitation targets for GHG emissions) to cost-effectively meet part of their reduction targets and to assist non-Annex I parties (developing countries under the Kyoto Protocol without legally binding emission reduction targets) in achieving sustainable development (UNFCCC 2012). In literature, it is argued that both objectives are contradictory, with the cost-effective reduction objective overshadowing the sustainable development goal. Amongst others, Sutter and Parreño (2007) find a trade-off strongly in favor of the cost-effective emission reduction objective, while neglecting the sustainable development goal. Based on a literature review, Olsen (2007) confirms that a trade-off between the CDM’s twin objectives exists and that when left to market forces, the CDM does not significantly contribute to sustainable development. Moreover, Pearson (2007) states that the CDM fails to promote sustainable development, a problem of which the cause is fundamental and stems from the CDM structure in which the search for least-cost carbon credits is the paramount consideration. Hence, he argues that most industrialized countries use the CDM merely to reduce their cost of compliance, searching for projects that deliver large volumes of cheap credits. Over the years, most issued CERs came from hydrofluorocarbons (HFC) and nitrous oxide ($N_2O$) projects (Table 1), which are argued to yield the least sustainable development benefits (Sutter and Parreno 2007; Olsen and Fenhann 2008).

Renewable energy projects on the other hand are less commonly implemented under the CDM, despite their large potential to contribute to sustainability. Especially solar technologies are underrepresented, claiming on average 0.05% of all the issued CERs (Table 1). Pearson (2007) states that questioning whether the CDM is promoting sustainable development can be framed primarily in terms of whether it is promoting renewables in developing countries. Del Rio (2007) encourages the deployment of renewable electricity projects such as solar PV, as -apart from contributing to the GHG emission reduction- they provide substantial local economic, social and environmental sustainability benefits to host countries. Kim et al. (2013) find that technologies whose primary benefits are sustainable development (such as solar PV) are more likely to be neglected under the CDM. The scarce amount of CER credits from solar projects mainly results from on-grid solar (96% of all registered solar projects are grid-connected installations). Since the deployment of the CDM, no more than 14 off-grid photovoltaic solar projects (all small-scale projects ) have been registered (UNFCCC 2013). On average, these small-scale projects are found to contribute to a slightly higher number of sustainable development benefits than large-scale projects. In particular, they deliver more economic and social benefits (Olsen and Fenhann 2008). Hence, in this research, we focus on small-scale rural PV technologies, which play a negligible role under the CDM.

**Table 1** Trend of CERs issued/issuing according to project type as a percentage of the total amount of CERs issued/issuing (UNFCCC 2014)

| Year | Hydro | Wind | Solar | Biomass | HFC | $N_2O$ | Methane | Other |
|---|---|---|---|---|---|---|---|---|
| 2006 | 5.92% | 3.49% | 0.00% | 13.75% | 59.94% | 7.80% | 6.31% | 2.79% |
| 2007 | 2.51% | 2.47% | 0.00% | 6.09% | 46.27% | 25.61% | 5.15% | 11.89% |
| 2008 | 3.53% | 4.35% | 0.00% | 2.56% | 56.43% | 22.18% | 7.39% | 3.55% |
| 2009 | 5.25% | 5.98% | 0.00% | 2.65% | 57.97% | 19.25% | 3.93% | 4.97% |
| 2010 | 8.63% | 8.18% | 0.00% | 1.28% | 36.07% | 31.44% | 4.80% | 9.61% |
| 2011 | 12.15% | 8.78% | 0.04% | 1.40% | 38.78% | 20.93% | 7.11% | 11.16% |
| 2012 | 16.36% | 12.98% | 0.03% | 2.59% | 30.06% | 15.31% | 9.54% | 13.12% |
| 2013 | 20.30% | 16.49% | 0.36% | 4.53% | 14.83% | 12.43% | 15.73% | 15.77% |
| Average | 9.33% | 7.84% | 0.05% | 4.36% | 42.54% | 19.37% | 7.50% | 9.11% |

The objective of this work is to assess the attractiveness of solar LED lighting projects under the CDM and to develop policy recommendations accordingly. To this end, we evaluate their economic and environmental performances by means of the mitigation cost, that is the average cost per ton $CO_2$ reduced. To calculate the mitigation cost, we quantify *(i)* the economic life cycle costs of the project and *(ii)* the amount of $CO_2$ equivalent emissions avoided by the project over its lifetime. The mitigation cost analysis allows ranking technologies or projects in order of decreasing cost of emissions abatement or hence in order of increasing attractiveness for the potential CDM project implementer. Low mitigation cost projects imply low economic costs as well as highly avoided $CO_2$ emission reductions, which are in turn rewarded with saleable CER units. Hence, projects with low mitigation costs are most attractive for the investors to implement, as they enable low-cost procurement of CER credits (Kim, Popp et al. 2013). The United Nations Framework Convention on Climate Change (UNFCCC) finds solar photovoltaics to be the most expensive technology deployed in the CDM, with an average mitigation cost of $326 per ton $CO_2$ equivalents (UNFCCC 2012). In this research, we evaluate the mitigation cost of small-scale rural solar PV projects. In particular, we compare “absolute” and “relative” mitigation costs. With absolute mitigation costs, we refer to the mitigation cost defined by the UNFCCC (2012), in which the complete omission of baseline costs is assumed. To calculate relative mitigation costs on the other hand, avoided baseline costs are deducted from project costs (Lazarus, Heaps et al. 1995).

In this section, we described the need for evaluating small-scale rural PV projects under the CDM by means of a mitigation cost analysis. The section “Methodology” demonstrates the method used, including the absolute versus relative costs of mitigation. In the “Case” section, we apply these methods to a small-scale rural PV project, *i.e.* solar light emitting diode (LED) lighting. Based on our findings, “Policy recommendations” are formulated in the fourth section. We end the paper with a “Conclusion and discussion” of the findings.

## Methodology: Mitigation cost analysis

### Absolute mitigation cost

To calculate the absolute mitigation cost, we assume complete omission of avoided baseline costs. This approach is used by the UNFCCC (2012), in which the methodology for calculating the mitigation costs of CDM projects is described as follows:

> *“The mitigation cost is the total cost of the project, including initial outlay of capital, the annual operational expenditure and revenues per CER expected for each project. As shown in equation 1 below, project mitigation cost is defined as the net present value of a project´s annual operations costs less its non-CDM related revenues (e.g. income from electricity sales for wind projects), plus the capital expenditures, all divided by the amount of GHG emission reductions it expects to achieve over its crediting period.” (p 93).*

$$MC(absolute)_i = \frac{\sum_{t=1}^{cp} \frac{(OC_{i,t} - R_{i,t})}{(1+r)^t} + I_{0,\mathrm{i}}}{\sum_{t=1}^{cp} A_{i,t}} = \frac{\sum_{t=1}^{cp} \frac{(OC_{i,t} - R_{i,t})}{(1+r)^t} + I_{0,\mathrm{i}}}{\sum_{t=1}^{cp} \mathrm{E_{b,t}} - \mathrm{E_{i,t}}} \qquad \text{(Eq. 1)}$$

Where:

$MC(absolute)_i$ is the absolute mitigation cost of project *i* (in \$/t $CO_2$eq);
*t* denotes a given year during the project crediting period;
*cp* is the length of its crediting period(s) (up to 10 or 21 years);
$OC_{i,t}$ is the operating cost of project *i* in year t (in \$);
$R_{i,t}$ is the non-CER revenue of project *i* in year t (in \$);
$I_{0,i}$ is the initial investment of project *i* (in \$);
$A_{i,t}$ is the abatement (expected emission reduction) achieved by project *i* in year t (in t $CO_2$eq), which is defined as the difference between the baseline emissions ($E_{b,t}$) and the project emissions ($E_{i,t}$) according to CDM baseline methodologies;
*r* is the discount rate (expressed as a decimal; 1% = 0.01)

As mentioned before, this definition implies the omission of the baseline costs, *i.e.* costs related to the baseline technology that are avoided due to implementation of the project. Further, the crediting period rather than the operational lifetime is used for the calculation, also in cases in which the operational lifetime exceeds the crediting period. The project participants may choose between two options for the length of a crediting period: *(i)* a “fixed” crediting period with no possibility of renewal or extension with a length of maximum 10 years or *(ii)* a “renewable” crediting period with single crediting periods of maximum 7 years which may be renewed two times at most (maximum 21 years). The amount of expected emission reductions is determined as the difference between baseline and project emissions, using prescribed CDM baseline methodologies. Note that the mitigation cost defined as such is calculated from the viewpoint of the project developer.

**Relative mitigation cost**

To calculate the relative mitigation cost, avoided baseline costs are deducted from project costs. This is according to the definition of Lazarus et al. (1995), in which the greenhouse gas mitigation cost of technology $i$ is defined as the economic cost per ton carbon dioxide equivalents ($CO_2$eq) avoided when using technology $i$ to replace the baseline technology $b$. The mitigation cost is considered from the project developer's point of view. To calculate this cost, we determine the GHG mitigation potential and the additional economic costs of the project technology $i$ as compared to the reference or baseline technology $b$ over the technologies' lifetime $t$ (Eq. 2). For purposes of comparison, we apply the terminology used in Eq. 1. The differences with the absolute mitigation cost in Eq. 1 are indicated in grey.

$$MC(relative)_i = \frac{\sum_{t=1}^{n}\frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}+I_{0,\mathrm{i}}-\sum_{t=1}^{n}\frac{(OC_{b,t}-R_{b,t})}{(1+r)^t}+I_{0,\mathrm{b}}}{\sum_{t=1}^{n}A_t} = \frac{\sum_{t=1}^{n}\frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}+I_{0,\mathrm{i}}-\sum_{t=1}^{n}\frac{(OC_{b,t}-R_{b,t})}{(1+r)^t}+I_{0,\mathrm{b}}}{\sum_{t=1}^{n}\mathrm{E_{b,t}}-\mathrm{E_{i,t}}} \qquad \text{(Eq. 2)}$$

Where:

$MC(relative)_i$ is the relative mitigation cost of project $i$ (in \$/t $CO_2$eq);
$t$ denotes a given year during the project lifetime;
$n$ is the operational lifetime of the project;
$i$ refers to the project implemented;
$b$ refers to the replaced baseline technology;
$OC_t$ is the operating cost in year $t$ (in \$);
$R_t$ is the non-CER revenue in year $t$ (in \$);
$I_0$ is the initial investment (in \$);
$A_t$ is the abatement (expected emission reduction) achieved by $i$ project in year t (in t $CO_2$eq), which is defined as the difference between the baseline emissions ($E_{b,t}$) and the project emissions ($E_{i,t}$) determined by means of a life cycle analysis (LCA) model;
$r$ is the discount rate (expressed as a decimal; 1% = 0.01)

According to this definition, the avoided baseline costs are deducted from the project's costs. In this research, the replaced baseline technology is determined according to the applicable CDM methodology for purposes of comparison with the absolute mitigation cost. Economic costs are calculated over the technologies' operational lifetime (rather than over the crediting period) by means of life cycle costing. To calculate the amount of emission abatement, we make use of life cycle analysis (LCA); a method to quantify the environmental impact of a product or service over their full life cycle (ISO 14044:2006). Moreover, this study uses an attributional LCA model. Hence, we make use of average values for current technologies, as available in the EcoInvent database. To calculate the mitigation cost correctly, both the economic analysis and the environmental life cycle analysis must relate to the same functional unit. Amongst others, this approach has been demonstrated by De Schepper et al. (2014).

## Case: Portable solar LED lanterns under the CDM

In our research, we focus on small-scale rural solar LED lighting projects, which play a negligible role under the CDM in spite of their large sustainability potential. In particular, we consider a case in Cambodia, where the electrification rate is merely 24% (IEA 2011) and the market for modern off-grid lighting is nascent (International Finance Corporation 2012). The Kamworks company is one of the few that provides off-grid lighting to local villagers. They produce and distribute portable solar lanterns a.k.a. “*The Moonlight*”. We note that a key challenge for solar lantern projects is the lack of infrastructure for ensuring maintenance of the systems, *i.e.* skilled personnel, materials, and tools. The Kamworks company imports technological parts in the country and assembles them locally. Moreover, the company hires local sales people and they educate villagers to ensure maintenance of the lanterns over the lifetime of the project, thereby creating new job opportunities. The case is hypothetical and did not apply for registration under the CDM. We discuss *(i)* The projects and methodologies approved under the CDM; *(ii)* A brief description, including economic and technical data; and *(iii)* The calculation of the absolute and relative GHG mitigation cost, including a sensitivity analysis of the results. As functional unit of our GHG mitigation cost calculation, we consider the provision of light of 100,000 households with typical lighting needs in Cambodia, *i.e.* the provision of lighting with a strength of 90 lumens for 3.5 hours a day, 365 days per year, during a period of 10 years (the lifetime of the project technologies). Hence, our functional unit totals 114,975 million lumen-hours over a 10-year time span.

## Approved CDM projects and methodologies

For portable solar LED systems, two CDM methods are applicable. In January 2003, the Approved Methodology for Small-scale CDM project activities (AMS) I.A “*Electricity generation by the user*” (UNFCCC 2012) was launched, applicable to renewable electricity generation such as solar, hydro, wind, or biomass gasification implemented to replace fossil-fuel-fired generation. In November 2010, a specific standardized baseline method AMS-III.AR for “*Substituting fuel based lighting with LED/CFL lighting systems*” was introduced (UNFCCC 2012). To date, no more than 12 solar LED lantern projects have been registered. Table 2 shows an overview of the registered solar LED lighting projects sorted by date. We note that since its introduction, eight out of nine solar LED lighting projects were approved under AMS-III.AR. Accordingly, in this research, we apply the approved baseline AMS-III.AR to determine the solar LED lantern’s absolute mitigation cost. We note that the solar lanterns under consideration fulfill the criteria required by this methodology, *i.e.* the project activity replaces portable fossil fuel based lamps with LED based lighting systems in residential applications, the project lamps are charged with a photovoltaic system and have a minimum lifetime of 10,000 hours with a warranty of more than one year, no more than five lamps per household -three to be precise- are distributed, and measures are limited to emission reductions of less than 60kt $CO_2$ equivalents annually. Note that this methodology assumes kerosene lanterns as a standardized baseline technology to be replaced by solar lanterns.

**Table 2** Overview of portable solar LED lantern projects registered under the CDM sorted by “Date”; “Reductions” are the estimated emission reductions in metric tonnes of $CO_2$eq per annum (UNFCCC 2013)

| Title | Methodology | Date | Reductions |
|---|---|---|---|
| Registered solar LED lighting projects | | | |
| Rural Education for Development Society (REDS) CDM Photovoltaic Lighting Project | AMS-I.A | 10/8/09 | 21,060 |
| D.light Rural Lighting Project | AMS-I.A | 30/10/09 | 30,052 |
| Barefoot Power Lighting Programme | AMS-III.AR | 25/7/12 | 9,749 |
| Tough Stuff Solar Panel and Lamp Sales Madagascar Project | AMS-III.AR | 9/8/12 | 25,704 |
| Nuru Lighting Programme | AMS-III.AR | 3/10/12 | 34,294 |
| Project to replace fossil fuel based lighting with Solar LED lamps in Africa | AMS-III.AR | 3/12/12 | 21,393 |
| CarbonSoft Open Source PoA, LED Lighting Distribution: Emerging Markets | AMS-III.AR | 24/12/12 | 3,968 |
| Bundled project on distribution of solar energy lamps and replacement of incandescent light bulbs with compact fluorescent lamps | AMS-I.A | 26/12/12 | 28,961* |
| Southern African Solar LED Programme | AMS-III.AR | 31/12/12 | 12,236 |
| TATS Solar Lantern Programme of Activities | AMS-III.AR | 31/12/12 | 13,823 |
| Greenlight Solar PV Lighting India | AMS-III.AR | 31/12/12 | 56,397 |
| CarbonSoft Open Source PoA, LED Lighting Distribution: Pan Africa | AMS-III.AR | 1/10/13 | 41,850 |

*This is the emission reduction attributable to the solar energy lamps

## Case description

Portable solar LED lanterns are considered an alternative for kerosene lanterns in developing countries. An estimated 1.06 million households in Cambodia use kerosene as their primary source for lighting. These are primarily poorer households (International Finance Corporation 2012). Hence, in this research, we consider kerosene lanterns as the baseline technology to be replaced by solar LED lanterns, that is in correspondence with AMS-III.AR of the CDM. Economic and technical data regarding the lanterns is presented in Table 3. The total light output of one solar lantern with a lighting strength of 30 lumens that is used 3.5h/day, 365 days/y, over a lifetime of 10 years equals to 383,250 lumen-hours. Hence, to provide the total of 114,975 million lumen-hours, 300,000 project solar lanterns *(N)* are distributed to 100,000 households.

**Table 3** Economic and technical data (provided by the Kamworks company in December 2013)

| | Kerosene lantern (base technology *b*) | Solar LED lantern (project technology *i*) |
|---|---|---|
| Economic data | | |
| Initial investment *($I_0$)* | Lantern excluding wicks: $0.70 | Lantern including battery: $15<br>Battery: $5 |
| Operational lifetime *(n)* | Lantern: 2y<br>Wicks: 0.5y | Lantern: 10y<br>Battery: 2y |
| Operating costs *(OC)* | Kerosene: 0.74$/l (International Finance Corporation 2012); use: 0.03l/h (UNFCCC 2012)<br>Wicks: $0.125 | Battery replacement: $5 |
| Crediting period *(cp)* | - | 7 y (UNFCCC 2012) |
| Discount rate *(r)* | 4% (European Commission 2009) | idem |
| Technical data | | |
| Light output | 45 lm (Durlinger, Reinders et al. 2012) | 30 lm |
| Light source | Fuel (0.03l/h) | 6 LEDs |
| Solar panel | - | 0.7 Wp, a-Si |
| Battery capacity | - | 2Ah |
| Battery type | - | 2x NiCd AA (1.5V) |
| Density | 0.8026kg/l (OECD/IEA 2004) | - |
| Size of the systems considered to provide the functional unit of 114,975 million lumen-hours over a 10 year time span | | |
| Number of lumen-hours provided per system | 114,975lm-h | 383,250 lm-h |
| Number of systems needed to provide the functional unit *(N)* | 1,000,000 | 300,000 |

## Greenhouse gas mitigation costs

***Absolute greenhouse gas mitigation cost*** We start by calculating the absolute GHG mitigation cost of solar LED lanterns by dividing the discounted economic costs by the expected emission reduction over the lifecycle of *N* lanterns according to Eq. 1. Additionally, as higher purchase barriers often constitute a huge barrier for implementation, we calculate the absolute mitigation cost when considering merely the cost of investment rather than the full life cycle costs. Economic parameter values of the numerator in Eq. 1 (operating costs $OC_{i,t}$, initial investment costs $I_{0,i}$, crediting period *cp*, and discount rate *r*) can be found in Table 3. Note that these are data per lantern, they must be multiplied with the number of lanterns *N* to obtain the full project costs. There are no operational revenues $R_{i,t}$ from electricity generation, as the project lamps are not grid-connected. Reduced emissions in the denominator of Eq. 1 are calculated as the difference between baseline and project emissions according to AMS-III.AR (UNFCCC 2012). The expected emission reduction $A_{i,t}$ is detailed in Eq. 3, which is adapted from Paragraph 24 in AMS-III.AR (note that references to *"Paragraph x"* in the remainder of this section refer to paragraphs in AMS-III.AR). In this equation, $N_i$ stands for the number of solar lanterns distributed (numerical value in Table 3) and $OF_{i,t}$ represents the percentage of project lamps distributed to end users that are still operating and in service in the year *t*. The latter is fixed to 100% for years 1,2, and 3. For project lamps that claim emission reductions for up to 7 years, ex-post monitoring surveys must be conducted to determine the percentage of project lamps that are still operating and in service in years 4, 5, 6, and 7. We assume in our analysis that this number equals to 100% throughout the whole lifetime of the product. We note though that assuming that all lamps are operational up to year 7 represents an overestimation of the actual number of lamps in service. Baseline emissions ($E_{b,t}$), *i.e.* avoided emissions from the equivalent baseline lighting system, are calculated according to Paragraph 18, which provides a default emissions factor of 0.092t $CO_2$eq per project lamp, assuming a utilization rate of 3.5h/day, 365days/y, and a fuel use rate of 0.03l/h for kerosene lanterns. Project emissions of solar lanterns ($E_{i,t}$) are nonexistent (Paragraph 21). Results are presented in Table 4. The first column of Table 4 refers to the different components of Eq. 1. In the following two columns, the absolute mitigation cost over the prescribed crediting period of 7 years and the hypothetical crediting period of 10 years are calculated.

$$A_{i,t} = N_i * \left(E_{b,t} - E_{i,t}\right) * (OF_{i,t}) \qquad \text{(Eq. 3)}$$

***Relative greenhouse gas mitigation cost*** In this section, we calculate the relative GHG mitigation cost of *N* portable solar LED lanterns according to Eq. 2. The project costs in the numerator of Eq. 2 are calculated identically to those in Eq. 1, with the only exception being the lifetime *t*, which is now assumed to be the operational lifetime *(n)* of 10 years rather than the prescribed crediting period *(cp)* of 7 years (Table 3). Additionally, this calculation requires determination of the baseline costs, *i.e.* the avoided costs of using *N* kerosene lanterns that can provide the equivalent amount of lighting. Economic parameter values of kerosene lanterns are provided in the first column of Table 3. Emission reductions $A_{i,t}$ in the denominator of Eq. 2 are calculated as the difference between baseline ($E_{b,t}$) and project emissions ($E_{i,t}$) by means of life cycle assessment. To this end, we updated the attributional LCA model described by Durlinger in (Durlinger, Reinders et al. 2012) and (Durlinger 2012). Ecoinvent v2.2 data was used to model the background data (Frischknecht, Jungbluth et al. 2007). The impact assessment method ReCiPe (Goedkoop, Heijungs et al. 2012) was used to generate characterized results. More precisely, this study applies the result of the mid-point impact category "Climate Change". The professional software SimaPro 7.2.2 (PRé consultants, Amersfoort, The Netherlands) was used to model the LCA and to generate results. For purposes of comparison with the absolute mitigation cost, we also calculate the relative mitigation cost according to Eq. 2 over a lifetime of 7 years, which is the maximum crediting period prescribed under AMS-III.AR. Results are listed in the last two columns of Table 4.

***Sensitivity analysis*** In order to verify the sensitivity on the deterministic values used in this approach, a Monte Carlo sensitivity analysis is conducted on the GHG mitigation cost considering lifecycle costs, assuming 500,000 trial runs. For each economic parameter value (Table 3) and for all environmental life cycle emissions, a triangular distribution is assumed with minimum and maximum deviations of -10% and +10% with respect to the assumed values. Results are presented in Table 4 (B). We indicate the range of GHG mitigation cost values and the sensitivity information as the percent of the mitigation cost variance due to the spread in the three most influencing parameters. Note that a negative (positive) sign indicates that the GHG mitigation cost will decrease (increase) with an increase of this parameter.

**Table 4** GHG mitigation costs of solar LED lanterns versus kerosene lanterns

| | Absolute (*cp* = 7 y) | Absolute (*cp* = 10 y) | Relative (*n* = 10 y) | Relative (*n* = 7 y) |
|---|---|---|---|---|
| **(A) MITIGATION COST ANALYSIS** | | | | |
| (1) Project investment costs (\$): $I_{0,\mathrm{i}}$ | 4,500,000.00 | 4,500,000.00 | 4,500,000.00 | 4,500,000.00 |
| (2) Project O&M costs (\$): $\sum_t \frac{(OC_{i,t}-R_{i,t})}{(1+r)^t}$ | 3,706,261.92 | 4,760,142.02 | 4,760,142.02 | 3,706,261.92 |
| (3) Baseline investment costs (\$): $I_{0,\mathrm{b}}$ | not applicable | not applicable | 584,279.92 | 485,917.78 |
| (4) Baseline O&M costs (\$): $\sum_t \frac{(OC_{b,t}-R_{b,t})}{(1+r)^t}$ | not applicable | not applicable | 46,411,356.74 | 34,344,357.03 |
| **(1)+(2)-(3)-(4) Additional project costs (\$)** | **8,206,261.92** | **9,260,142.02** | **-37,735,494.64** | **-26,624,012.89** |
| (5) Project emissions (t $CO_2$eq): $\sum_t E_{i,t}$ | 0.00 | 0.00 | 1,602.00 | 1,518.00 |

| | | | | |
|---|---|---|---|---|
| (6) Baseline emissions (t $CO_2$eq): $\sum_t E_{b,t}$ | 193,158.00 | 275,940.00 | 283,605.00 | 198,523.50 |
| **(6)-(5) Emission reductions (t $CO_2$eq): $\sum_t A_t$** | **193,158.00** | **275,940.00** | **282,003.00** | **197,005.50** |
| **((1)+(2)-(3)-(4))/((6)-(5)) *GHG MC LCC ($/t $CO_2$eq)*** | ***42.48*** | ***33.56*** | ***-133.81*** | ***-135,14*** |
| ***((1)-(3))/((6)-(5)) GHG MC $I_0$ ($/t $CO_2$eq)*** | ***23.30*** | ***16.31*** | ***13.89*** | ***20.38*** |
| **(B) MONTE CARLO SENSITIVITY ANALYSIS** | | | | |
| Range($/t $CO_2$eq) | 35.49 to 50.87 | 27.98 to 40.24 | -186.04 to -93.68 | -190.07 to -92.38 |
| Sensitivity with respect to… | Kerosene emissions (-67.7%)<br>$I_0$ solar lantern (+19.0%)<br>Battery cost (+12.8%) | Kerosene emissions (-67.7%)<br>$I_0$ solar lantern (+16.7%)<br>Battery cost (+14.8%) | Fuel use rate (-34.8%)<br>Cost of kerosene (-34.8%)<br>Kerosene emissions (+23.4%) | Fuel use rate (-34.8%)<br>Cost of kerosene (-34.8%)<br>Kerosene emissions (+21.3%) |

***Results*** From our analysis in which we compared absolute and relative GHG mitigation costs of solar LED lanterns, we conclude the following: It is a major difference whether or not baseline costs are included. The absolute mitigation cost assumes the complete omission of baseline costs, even though the avoided costs of kerosene lanterns are approximately 5 times higher than those of solar lanterns to provide the equivalent amount of lighting. Moreover, sensitivity analysis of the relative mitigation cost indicates that the baseline costs are the most important parameters to determine the mitigation cost. This provides a clear motivation for using relative rather than absolute mitigation costs to assess the attractiveness of projects. Nonetheless, the UNFCCC defined and applies the absolute mitigation cost for this purpose. They recognize however that baseline costs can be significant for many projects, and that the avoided costs of fossil-fired generation render renewable energy projects viable despite their high mitigation costs (UNFCCC 2012). Indeed, in our analysis of the solar LED lighting, absolute mitigation costs are found positive while relative mitigation costs are negative. The sensitivity analysis indicates that these signs are maintained despite maximal variations in the parameter values between +10% and -10%. Note that a negative sign in this case means that replacing kerosene with solar LED lanterns provides net benefits to society, with the financial benefits outweighing the costs even before considering the value of reduced emissions. A second difference is the use of a limited crediting period under AMS-III.AR. Moreover, AMS-III.AR restricts the crediting period to a maximum of 7 years, while Kamworks assures a solar LED technology operational lifetime of 10 years. Avoided kerosene (baseline) emission is an important parameter in determining the mitigation cost, particularly in determining the absolute mitigation cost. This points to the importance of providing a good estimate of kerosene emissions under AMS-III.AR. Kerosene emissions according to AMS-III.AR (193,158 t $CO_2$eq) deviate no more than 2% from the emissions assessed using our LCA model (197,006 t $CO_2$eq), assuming equal utilization, fuel use rates, and lifetimes. We note though that in reality, results can differ due to other fuel consumption rates. Furthermore, as our LCA indicates that project emissions (1,518 t $CO_2$eq) represent less than 1% of avoided baseline emissions (198,524 t $CO_2$eq), it seems reasonable to assume that they are negligible, as is the case in AMS-III.AR. Finally, we note that the purchase price of the solar lanterns (+16.7%) and the batteries (+14.8%) -which constitutes a huge barrier for widespread implementation- indeed has an important impact on the mitigation cost. Nonetheless, the sensitivity analysis indicates that the avoided kerosene emissions have the greatest impact on the mitigation cost (-67.7%).

## Policy recommendations

Despite their large potential to lower the costs for local villagers while decreasing GHG emissions, deployment of solar LED lighting projects in developing countries is hampered by elevated initial investment costs. Hence, we stimulate the uptake of these projects under the CDM. We encourage continuing the use of mitigation costs -in particular relative mitigation costs- to make an ex-post evaluation of the attractiveness of CDM projects. This ex-post evaluation is useful for project implementers as well as for policy makers to verify which projects allow the procurement of

CER credits in an economically feasible manner. Based on our mitigation cost analysis, we formulate the following recommendations for CDM policy makers: First, specifically for rural renewable electricity projects, we point to the importance of considering avoided baseline costs by creating an additional revenue stream to ensure the economic project viability, which is a necessary condition for project implementation. We illustrate this idea in Figure 1: Under the CDM, a project developer implements a project in the host country in order to receive CER credits delivered by the CDM Executive Board. The CER credits are sold to an Annex I entity; a developed country who can use the credits for compliance. To ensure climate integrity, the project must pass through vigilant approval, monitoring and evaluation procedures that create additional transaction costs. In our research, we focus on costs and revenues related to the technologies; costs and revenues inherent to the CDM structure (*e.g.* transaction costs and CER revenues) fall beyond the scope. Operational revenues might consist of income from the electricity sale of on-grid wind or solar projects, in which generated electricity is directly fed into the national grid and thus easily quantifiable. In case of small-scale rural solar projects however, generated electricity is stored temporarily in batteries and is then used by the local villagers, who reap the benefits from project implementation as they no longer have to bear the costs from (more polluting) alternatives. Hence, the economic benefits of avoided baseline costs (*e.g.* the avoided costs of kerosene and diesel generators) accrue to the villagers rather than to the project developer, rendering the project economically unviable for the latter and hence hindering project implementation under the CDM. We argue that in this case, an additional revenue stream should be created, representing avoided baseline costs. Our analysis indicates that avoided baseline costs are often five times more expensive than the costs of project implementation. To ensure economic viability, it is in this case sufficient that approximately one fifth of these economic benefits are returned to the project developer. The remaining benefits accrue to the end user, creating a win-win situation for both parties. Despite the fact that the creation of a revenue stream of avoided baseline costs is not addressed in the CDM methodologies, we note that both registered SHS projects and one of the registered solar LED lantern projects already include such a revenue stream, in the form of a monthly or annual operational rent.

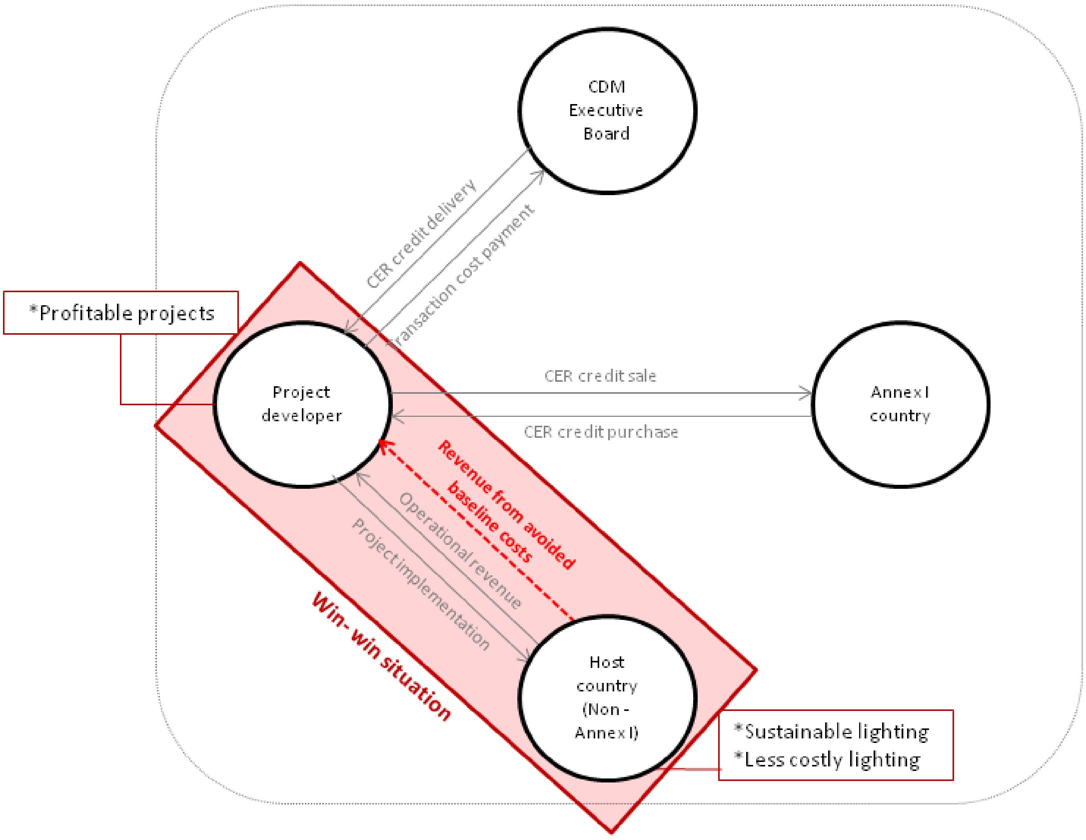

**Figure 1** CDM working principle

Second, we discourage the use of limited time periods during which CERs can be obtained. While we recognize the Board's concern of inferior products that will no longer be operational after *t* years, we argue that limiting the crediting period undermines the search for superior technologies. Moreover, by fixing an absolute time limit during which CER credits can be obtained, investors have no motivation to invest in longer living -more expensive- technologies and hence technological development is being countered. It is the mandatory use of the monitoring methodology, which imposes ex-post surveys to determine the percentage of project lamps operating and in service in year *t*, that should discourage investors to file deceiving lifetimes.

Third, we encourage the use of standardized baselines under the CDM to avoid misuse of the system by manipulating baseline emissions. For solar LED lanterns, a good estimate of the avoided baseline (kerosene) emissions is given in AMS-III.AR. Based on the results of our sensitivity analysis, we point to the crucial importance of providing a good estimate of this baseline. Besides countering the CER manipulation, the use of standardized baseline methodologies helps lowering transaction costs (Hogarth 2012). In this regard, Spalding-Fecher and Michaelowa (2013) also emphasized that standardized baselines in the CDM should be mandatory. Nonetheless, a limited amount of flexibility should be maintained. Examples include standardized baselines per country or region and the possibility to use different values, as long as justification is provided.

## Conclusions and discussion

The results of this paper encourage the use of relative rather than absolute mitigation costs to assess the attractiveness of CDM projects**.** This implies that avoided baseline costs are to be taken into account, often rendering the projects economically viable. Due to the inherent CDM structure however, economic viability -which is a necessary condition for project implementation- is not automatically realized. This is a mere structural problem, which can be altered to a win-win situation for both parties by including guidelines to stimulate an additional revenue stream of the avoided baseline costs. Correcting this metric accordingly will especially influence the evaluation of small-scale renewable energy projects, as the avoided costs of fossil fuels render these projects profitable. In case of lighting, this would correspond to a "lighting as a service model", in which the project developer will pay upfront lighting costs and is compensated through a performance contract, *i.e.* the energy savings due to the new lighting technology. It has already been demonstrated in literature that these projects make a significant contribution to the sustainability of host countries. When reconsidering the mitigation cost as such, the CDMs twin objectives -*i.e.* assisting at cost-effective emission reduction and contributing to sustainable development- are more likely to be reconciled rather than opposed.

Our analysis demonstrates that solar LED lanterns are cost-effective projects to reduce greenhouse gas emissions from kerosene lanterns in Cambodia, as indicated by the negative mitigation cost. We note however that this conclusion may vary for different locations, depending on the amount of solar insolation and the infrastructure (skilled personnel, materials,…) available on the site. While this research aimed at evaluating the attractiveness of solar LED lighting projects under the CDM, additional research is required to assess whether other potential projects (*e.g.* solar home systems, hydro, wind,…) could be more attractive for CDM investors to pursue.

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