Life Cycle Assessment of Off-Grid Lighting Applications: Kerosene vs. Solar Lanterns

by

Shreya H. Dave

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ABSTRACT

Access to electricity in developing countries is minimal and if available, often unreliable. As a result, fuel-based kerosene lighting is the most common solution to lighting necessities. However, kerosene combustion affects indoor air quality and relies on a non-renewable fossil fuel subject to price volatility. Thus, solar lanterns are being introduced to developing markets, but incur their own energy and emissions intensity from more complex manufacturing processes and requirements. Life cycle assessments examine the energy required and the emissions released over the entire existence of a product or process to allow for quantitative comparison among technology options.

The results from a "cradle-to-user" life cycle assessment of the lighting options are displayed in Figure 1 below.

	Tin Lamp	**Hurricane Lamp**	**Solar Lantern**
Total energy input (MJ)	1.1E+03	3.9E+03	2.2E+03
CO2 emissions (kg)	7.4E+01	3.9E+02	2.4E+02
Particulate emissions (kg)	9.8E+00	4.5E+00	1.6E-03
Total emissions per lumen (kg/lumen)	1.1E+01	6.1E+00	7.0E-01
Lumen per energy input (lumens/kJ)	7.1E+00	1.7E+01	1.6E+02
Lumens per dollar cost (lumens/$)	0.046	0.074	3.500

Figure 1: Summary of results

The values reported do not clearly indicate that it is a sustainable decision to transition to solar-based lighting from the conventional use of kerosene combustion. However, understanding the data presents further opportunities for reducing the impact of lighting. The economic payback time of a solar lantern, the distribution emissions in location and time, and the challenges of implementation on a large scale are among these critical review considerations.

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1 Introduction

Solar cell life cycle analysis has been conducted in great detail by manufacturing experts in the field of photovolatics. *Life cycle assessment* (LCA) refers to the anyalysis of inputs and byproducts in each of the production, utilization, and scrapping phases of a product's life. Cumulative inventory is made for emissions of greenhouse gases, toxic heavy metals, and other pollutants, and energy inventory is calculated per unit of product. Companies use LCAs to streamline their manufacturing processes and to promote an inherently sustainable product. In this study, we will use LCAs to determine the true impact of a product throughout its life and to make a comparison across various options.

In the case of solar electricity generation, a significant amount of energy is required for the manufacturing and distribution of solar cells and modules. It is therefore crucial to ensure that the panel generates net positive clean energy to more than offset the inputs required to achieve the capability of generating clean energy. However, photovoltaic LCAs tend to neglect the circumstance of utilization in their studies, making the results abstract and applicable only to the generic case.

The MIT Future of Solar report has chosen to take the opposite approach. Structuring utilization of solar energy by application, we will compare the conventional alternative to a solar replacement over each lifecycle. Specifically we will address off-grid lighting, small-scale mini-grids, water pumping, and refrigerators for health clinics. In each case, the solar option must perform as well or better than the conventional alternative (for example, intermittency issues may need to be addressed with storage). This paper will use life cycle analysis to quantify the environmental impact of solar lanterns as a replacement for fuel-based lighting, the most common of which are kerosene lamps. It will later be revised to be incorporated in the analysis of the Future of Solar Study of developing countries, markets and applications.

Life Cycle Assessment

A life cycle assessment takes into consideration the inputs and energy requirements of all stages of a product's life. The *production* phase includes the energy and material inputs for manufacturing the product. Often, and especially in developing countries, the only byproducts of the production phase are emissions because scrap materials are re-used in the processing phase to cut costs. During the *use* phase, some products – for example, newspapers – do not consume or emit anything regardless of the number of times it is read. However a car consumes gasoline (energy) and emits carbon dioxide among other pollutants continuously and until the end of its life. Finally, the *scrapping* phase quantifies the disposal of material produced in the production phase less the components that are recyclable in some form. If energy is required to separate components or to dispose of toxic waste, it is included in the scrapping phase. A schematic for a generic product is shown in Figure 2.

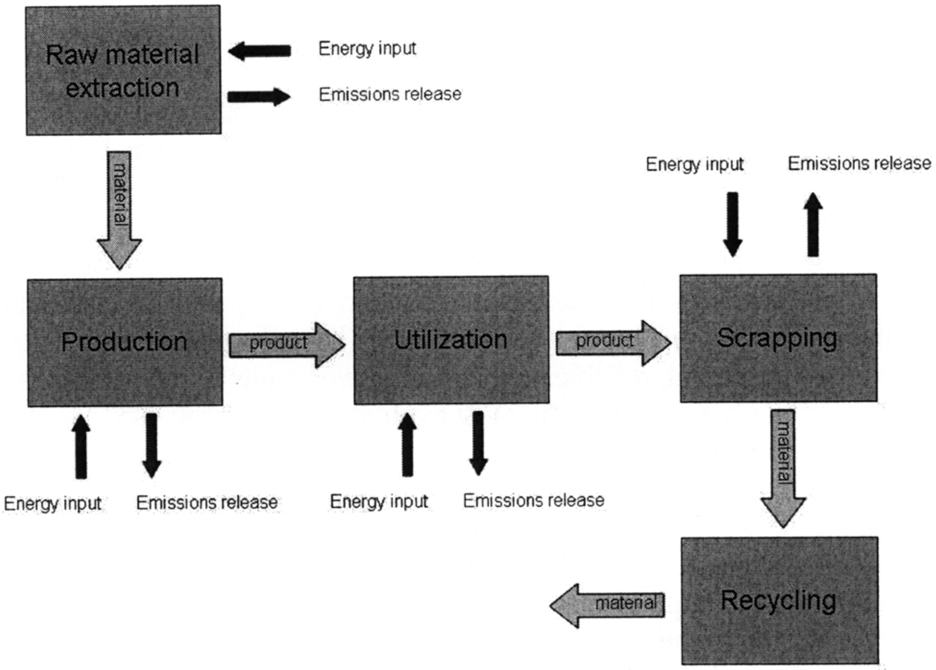


Figure 2: Generic product life cycle assessment process model.

Purpose of this Study

This study compares the life cycle input and byproducts of a solar lantern to that of a lamp. The kerosene lamps are what would be replaced if solar lanterns were successfully introduced to markets in developing countries where electricity is not ubiquitous or, if available, reliable. Lanterns are one of the most common applications of distributed off-grid solar in developing countries, with projects run by the World Bank, UC Berkeley, Lawrence Berkeley National Laboratories, and Columbia University, among others. Further, private companies such as Sollatek with its Glowstar lantern, are entering the space of solar lighting devices. This study aims to answer questions of impact when solar lanterns are implemented at substantial levels of penetration. Specifically, the following issues will be addressed:

- Silicon demand: quantity
- Battery disposal waste
- Net CO_2 emissions (positive or negative)
- Energy input
- Economic payback time
- Discount rate applied to emissions

Further conclusions may be derived from the data that is reported.

Background to this Study

The Life Cycle Assessment balance has been calculated using a variety of data sources. In the absence of the ability to do field work to substantiate the data inputs, we verified our choices with as many sources as possible to determine average and generic numbers for regions. We have focused the regions of kerosene lantern use to Sub-Saharan Africa and rural India. Data sources are mixed, but this study integrates many studies to determine the overall impact of kerosene and solar lanterns. In some cases, as in for photovoltaic panels or lead-acid batteries, we have "piggybacked" on more thorough LCAs than we have the resources to calculate. We have chosen the most transparent, reliable, and conservative results to report upon and have cited all relevant sources. Wherever possible, the most explicit data has been used (i.e. the data with the greatest resolution). In addition to using available databases for life-cycle energy and emissions data, we have obtained consumption and technical specification data from a number of organizations affiliated directly with off-grid solar lighting.

Lighting Africa is a joint World Bank and International Financing Corporation (IFC) project that is facilitating the implementation of affordable solar lighting solutions in Sub-Saharan Africa. According to the World Bank, African households spend up to 30% of their disposable income on the fuel-based lighting. Solar lanterns, meanwhile, provide light with no additional cost to the user for its lifetime. Lighting Africa works to facilitate, develop, and strengthen the solar lighting market in rural regions, providing a sustainable technology-based industry for local inhabitants. By providing market research resources, entrepreneurial experience, and a global perspective, Lighting Africa aims to create a level playing field rather than to endorse one specific technology[1].

The Lumina Project also works in conjunction with the World Bank to "cultivate technologies and markets for affordable, low-carbon, off-grid lighting in the developing world." Interdisciplinary research teams allows the group at Lawrence Berkeley National Labs to address technological, societal, and political issues that face companies entering the developing world markets. The group engages students with new perspectives, and engages in a variety of research techniques both within the lab and out in the field to study the current and potential status of lighting in developing countries[2].

The United States National Renewable Energy Laboratory (NREL) has collected a database of Life Cycle Inventory (LCI) data to provide information to answer life cycle questions. With partners such as Franklin Associates, NREL has compiled a set of cradle-to-gate material and energy flow that is available for public use[3]. Although all the data is all US-specific, this research was invaluable to our calculations.

Please be advised that this study is not affiliated with any of these projects, although we have communicated with all for advice and data points. The material published by each group have been extremely useful in understanding consumption patterns and typical specifications for lighting requirements, use, and technology. We hope to enable further communication between the MIT Future of Solar study and these organizations as we refine our data inputs and calculations in the future.

2

Kerosene Lamps

Fuel-based lighting, or light sources that do not require electricity, maintain prevalence in many of the world's developing countries. In India, although 80% of villages are electrified, only 44% of rural households have access to electricity[4]. The Ministry of Power in India has established programs to implement rural electrification, but deem a village "electrified" if only 10% or more of the households are connected[5]. As a result, 42% of homes in India use kerosene as fuel for lighting[6]. Assuming 2 kerosene lanterns per home – one for the main living area and one for use in outhouse toilets – this means 44.5 million kerosene lanterns are in use throughout the country[7]. One household spends about 88 USD equivalent per year in kerosene fuel costs, approximately equal to the average monthly income per household of the entire country[8],[9].

In Sub-Saharan Africa, about 79% of households are reported to be using "tin" kerosene usually lamps fashioned locally by hand from scrap metal. In Sauri, a region of Sub-Saharan Africa, schools provide study centers where kerosene light is used. One schoolteacher reports that 90% of students utilize this lit area 5 days a week. Some of the poorer children cannot afford kerosene for studying at home and in some schools, morning study hours are also provided. The operating cost for these study centers is a function of the cost of kerosene. Further, Kenyans report of nighttime muggings at street vendors, unsafe conditions when using the outdoor toilet, and the inability of children to study after dark[10]. For the 1.6 billion people worldwide without access to electricity, safety and educational productivity are severely compromised.

In both countries, a variety of kerosene-based lighting devices are utilized. These include kerosene wick lamps, hurricane lanterns, kerosene petromax, and non-pressure mantle lamps. We have qualitatively determined that the most prevalent lamps in Kenya are simple kerosene wick lamps. Hurricane lamps are about ten times as expensive but also provide better quality light and are therefore more desirable to those who can afford it[11]. The exact distribution of lamp types is difficult to ascertain, and so analysis has been conducted on each to show the range in values.

The tin lamp is a simple "chimney lamp," in which a kerosene-soaked wick burns through a chimney. These are made by hand locally and with scrap materials[12]. In addition to a more complex manufacturing process for the hurricane lantern, the two lanterns differ in the amount of kerosene consumed per hour and the amount of particulate matter emitted from the combustion process, as shown in Table 1, and sketched in Figure 2. The hurricane lamp can regulate the airflow to the flame, allowing for a cleaner burning wick if adjusted correctly.

	Tin Lamp	Hurricane Lamp
Light emission[13] (lumens)	7.8	67
Cost (USD)	$1, made locally	$10, imported
Kerosene consumption (litres/hour)	0.008	0.042
Particulate emission (mg/hour)	535	295

Table 1: Major differences between "tin" and hurricane kerosene lamps.

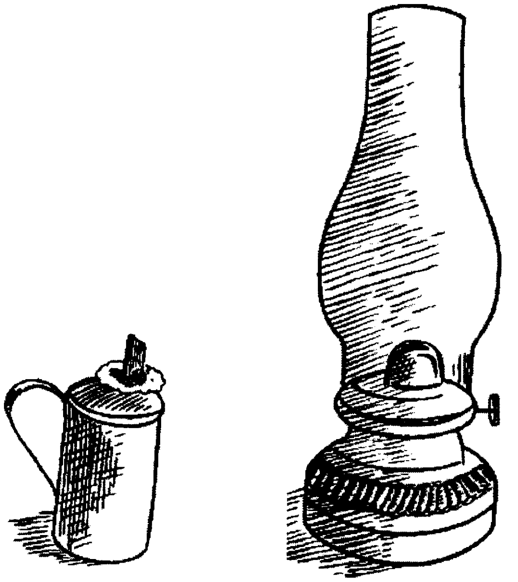


Figure 3: (left) A "tin" lamp and (right) a hurricane lamp.

The particulate matter generated by kerosene as a liquid fuel results in health problems associated with poor indoor air quality. The devices are also often unstable and tipping of the lamp can result in fire. Finally, a significant amount of heat is generated from the lighting source, an undesirable characteristic in the hot-humid climates of both India and Sub-Saharan Africa. Heat is not a standard byproduct, or output, that can be quantified from the data available, but is certainly an externality that should be noted.

Because the kerosene fuel consumption has the greatest impact on the life cycle results and the "tin" lamps are locally made with entirely scrap material, it is reasonable to assume that the life cycle impact for production is negligible compared to the fuel production and consumption.

Product Process Model

Functional Unit

All Life Cycle Analyses require a functional unit of calculation. This indicates the "*per what*" of energy consumption and emission creation. With no substantial data for the lifetime of kerosene lamps, we have assumed that the functional unit is light providers for one family for 10 years. From qualitative market assessment, we know that 2 kerosene lamps are used per family for a total of 5 hours of light per day. We have assumed that each lantern will last for 10 years at which point it will not be reparable. While some materials may be reused, the lamp itself will not. Meanwhile, kerosene and wicks are consumable inputs and will be summed over the 10 years.

System boundaries

Each type of kerosene lamp will be analyzed from the manufacturing of the product to the user. This is different from the standard "cradle-to-gate" often used for life cycle analyses because this study wishes to encapsulate effects of combustion kerosene inside homes. This study will not consider the effects of disposal, but an extension of the end-of-life boundary may be valuable for a future revision.

Data quality requirement

As a first order discussion of the life cycles of kerosene lamps and solar lanterns, the data quality requirement is relatively low. In some cases, where data is not available for production mechanisms in the country of interest, United States data has been substituted. Since the questions to be answered are ones of scale, rough values are sufficient.

Critical review considerations

The following aspects will be taken into account as a second order evaluation: economic payback time and discount rates on both the investment of the lamp and emissions over time. The same evaluation will be conducted for the solar lanterns with which these kerosene lamps are being compared.

Material and Energy Inputs

The hurricane lamp evaluated in the following life cycle assessment has the three components listed below in Table 2. The housing consists of the lamp's metal base, frame, and air regulation valve. The kerosene and wick are both consumable products, required for generating light through combustion. The tin lamp also has the three components, but the quantifiable inputs for the housing are considered negligible.

	Housing	**Kerosene**	**Wick**
Specifications	1 kg, aluminum	crude oil, 0.042 litres/hour	cotton, 2.5 g/hour
Raw Material Extraction	Secondary Material, n/a	Yes	Yes
Component Manufacture	Yes	Yes	Lack of Data, negligible
Component Assembly	Lack of Data, negligible	n/a	n/a
Transportation	Yes	Yes	Lack of Data, negligible
Utilization	n/a	Yes	Yes
Recycling	No	No	No
Disposal	No	No	No

Table 2: Component data consideration for the following life cycle assessment of a kerosene lamp.

For kerosene and wicks, energy input and emissions are consumption-dependent. In this case, the consumption depends on the hours of light required by the family's lighting source. Qualitative market research from the World Bank's study of Kenya indicates that, on average, one family uses two lamps for a total of five hours of lighting per day. This value, 1825 hours per year, has been used as a baseline for consumption of these expendable components.

Housing

Since we were not able to confirm figures with Chinese manufacturers of hurricane lamps, we based our calculation of material input on the hurricane lanterns commercially available to consumers in the United States. We therefore assumed that the weight and composition of the mass-produced housings is approximately 1 kilogram of aluminum[14].

We further assumed that the aluminum was shape-casted, and ignored the energy and cost of tooling the manufacturing plant. This is justified because kerosene lamps are mass produced, and the allocation of tooling would be insignificant for this first order calculation.

The data for shape casting secondary aluminum ingots was obtained from the NREL LCI database[15]. Since there are no purity requirements for the secondary aluminum for use in kerosene lamp housings, we assumed negligible production inputs for creating the secondary ingots. In total, the energy input for 1 kilogram of shape-casted aluminum is 24.6 MJ. The energy input is primarily natural gas combustion in an industrial boiler. As a result, carbon dioxide emissions to air compromise the majority of emissions from shape-casting (by a factor of 100, as shown in Figure 4 below). These are the critical pollutants that the life-cycle analysis will track over all components of the kerosene lamp and compare to those of the solar lantern.

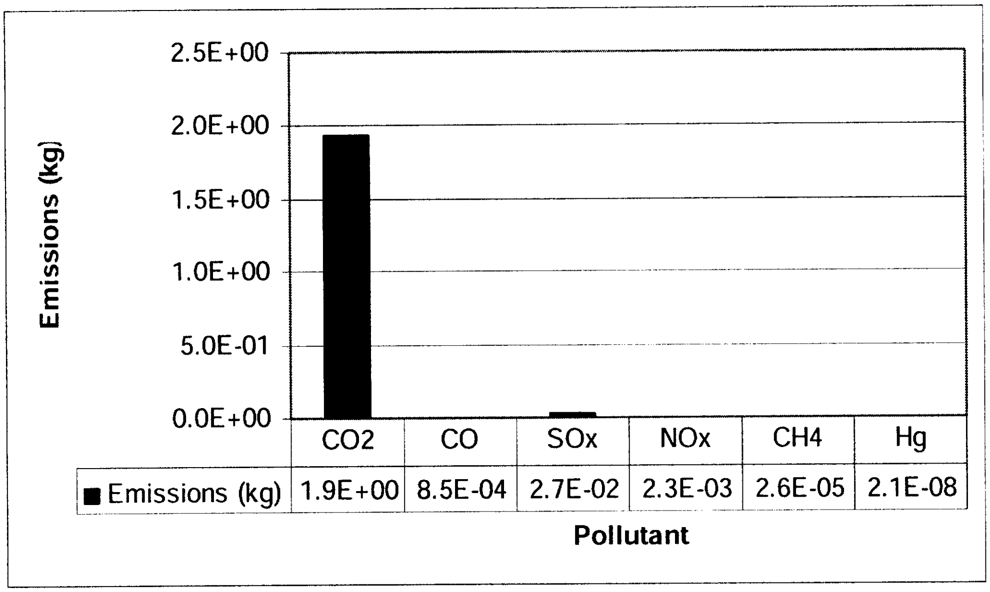


Figure 4: Emissions from shape-casting 1 kg of secondary aluminum ingot.

The tin lamp described in the introduction is a locally made cylinder and base of scrap metal that resembles a can. The kerosene is contained in this can, and the wick protrudes through a chimney made of the same scrap metal. The wick soaks up the kerosene from the base and the flame is open and exposed, much like a candle. The cost of materials is essentially zero, and the energy input for manufacturing is worker time and the open fire used to heat the metal and seal it together. The manufacturing of these lamps is not institutionalized and there is no quantitative data that can be derived from the sources available. Although we will recognize qualitative benefits of local employment and income, we have assumed the manufacturing energy input and emissions release to be negligible for the tin lamp.

Kerosene

The liquid kerosene that is used to power these fuel-based lamps is the most energy intensive and expensive component of the lamps' life cycles. The tins lamps, which are in fact more common in Kenya, consume 14.6 litres of kerosene per year. In 2008 prices, this comes to about $17 USD per year[16]. For a family that can afford a hurricane lamp, the fuel consumption is higher, at 76.65 litres per year, or $90 worth of kerosene. Either way, this can be up to 30% of the disposable income (income not used toward food and shelter) of an entire household. The hurricane lamps consume nearly five times as much kerosene, totaling 76.6 litres per year and costing a household $88 per year[13,16].

The simplified kerosene process model is shown in the following flow diagram.

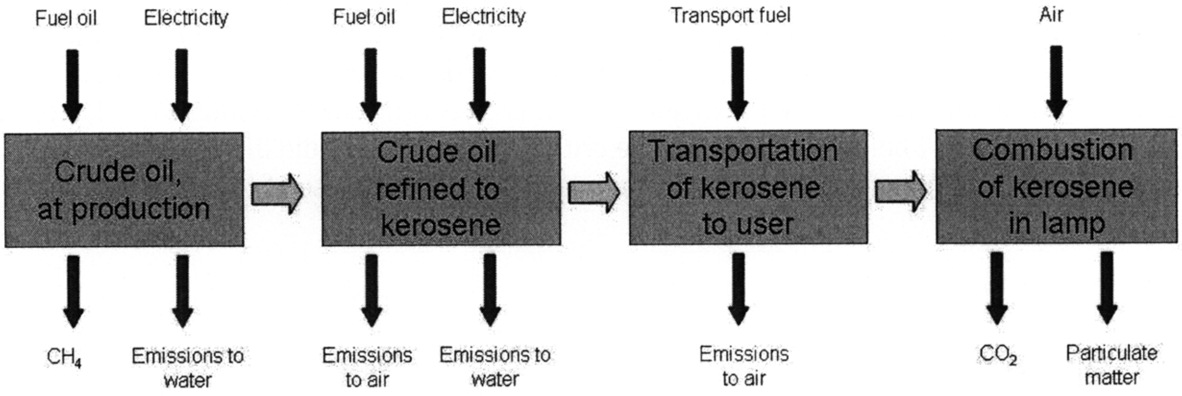


Figure 5: Kerosene process model, simplified.

The data used for crude oil production, refining, and transport is again from NREL's LCI database. Because this dataset is location specific to United States averages, there are inconsistencies with our model. For example, the likelihood of the oil production required to supply Sub-Saharan Africa with kerosene being in the United States is low. However, rather than making assumptions to adjust the US data, it has been used in all following calculations. This action is justified based on the following:

- The operations in other countries, specifically Africa, may be as efficient and use a similar energy input, but due to a different fuel mix would probably emit more pollutants. The United States has air quality standards that differ from international operations and probably do not exist for oil producers in Africa.
- Kerosene is already the greatest contributor to the hurricane lamp's life cycle energy input and pollutant emission. Since the data is likely to be adjusted such that the impact is even greater, it may remain for a further revision of the calculation.

Kerosene is not the only product that results from crude oil production and refining. Thus, only a portion of the energy input and emissions output must be allocated to kerosene. The allocation was determined by the composition of the product stream from crude oil refining. Using higher heating values of the various product streams, the relative energy value of each component to the whole product was calculated and is shown in Figure 6. From this, the allocation of energy input and emissions output from kerosene was designated as 0.10.

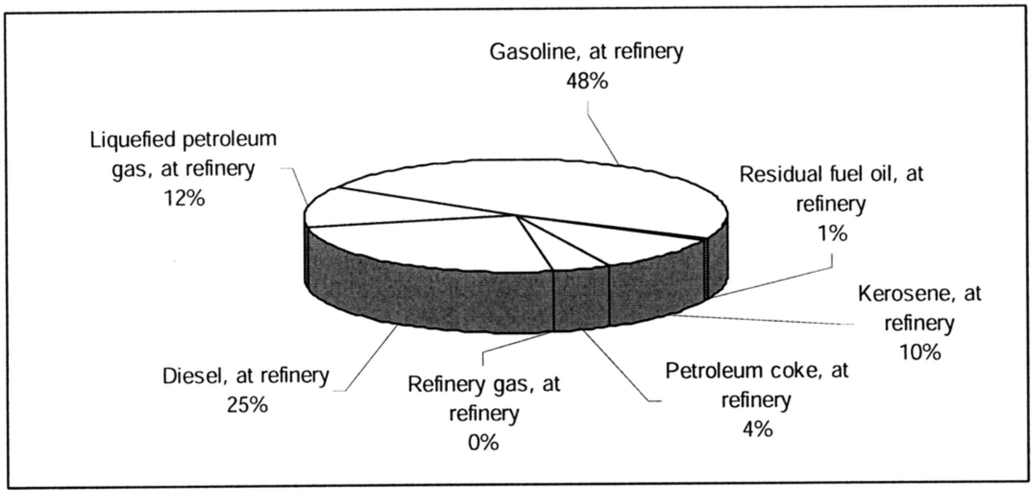


Figure 6: Products from crude oil refining.

The energy input for the production, refining and transport of kerosene is either in the form of fuels – diesel, natural gas, residual fuel oil, gasoline, or other transport fuels – or electricity. From NREL's LCI data, we can quantify the relative significance of each form of energy input, and the amount required at each stage, shown in Figure 7.

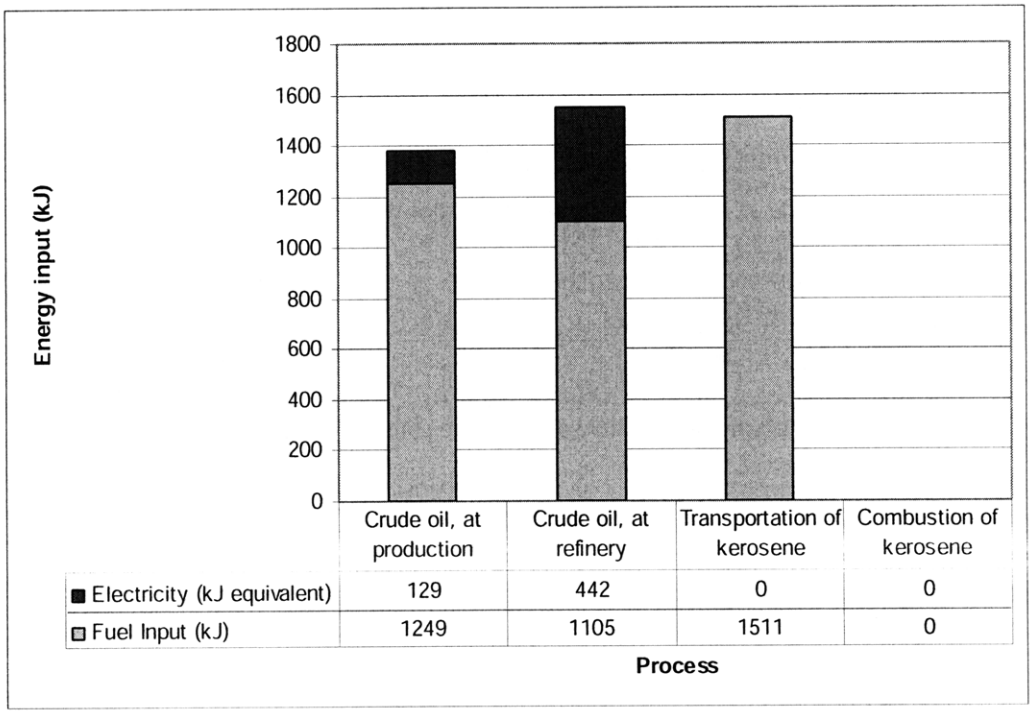


Figure 7: Energy input in kJ per litre of kerosene produced.

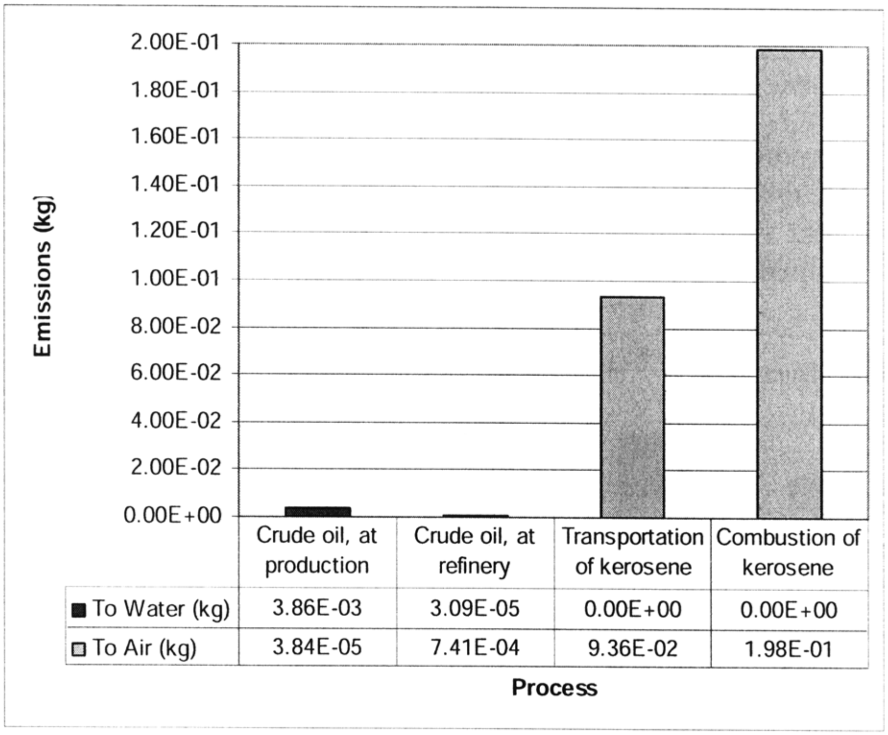
The emissions from each of these processes are released either to the air or the water. Again, the 0.10 allocation factor has been applied in order to calculate kerosene's share of the emission output.

For kerosene combustion, complete combustion was assumed according to the stoichiometric equation shown below. Thus, 14 moles of carbon dioxide is produced for each mole of kerosene ($C_{14}H_{12}$), which can be converted by into absolute mass emitted per litre of kerosene.

$$C_{14}H_{12} + 17(O_2 + 3.76N_2) \rightarrow 14CO_2 + 6H_2O + 63.92N_2$$

Equation 1: Complete combustion of $C_{14}H_{12,}$ a common composition of kerosene used in fuel-based lighting.

The kilogram total of pollutant emissions is 0.296 kg per litre kerosene combusted in a fuel-based lantern[a]. The distribution of emissions is shown in Figure 8.



	Crude oil, at production	Crude oil, at refinery	Transportation of kerosene	Combustion of kerosene
■ To Water (kg)	3.86E-03	3.09E-05	0.00E+00	0.00E+00
□ To Air (kg)	3.84E-05	7.41E-04	9.36E-02	1.98E-01

Figure 8: Emissions distribution to water and air per litre of kerosene combusted in a kerosene lantern.

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[a] This assumption of complete combustion was made in order to be able to make a calculation. In reality, the user adjusts the air intake valve of the lamp to determine amount of air (oxygen) that enter the reaction. We assumed that the user would adjust to the optimal condition in order to save on fuel costs. This assumption was approved as reasonable by professor Ahmed Ghoniem of the Department of Mechanical Engineering at MIT.

Wick

The wicks used in kerosene lanterns vary in size and shape, but are typically made of cotton and are, on average, 1 inch in diameter. The manufacturing phase of the actual wick could not be considered due to a lack of data for industrial processes. However, it may be assumed that wicks are often hand spun from cotton roving, in which case the energy input is in human power and the emissions are zero. For just the cotton production – which includes seed production, tillage, fertilizer and pesticide application, crop residue management, irrigation, and harvesting, but not processing of the raw materials – the energy input is a mixture of fuel and electricity inputs, as shown in Figure 9.

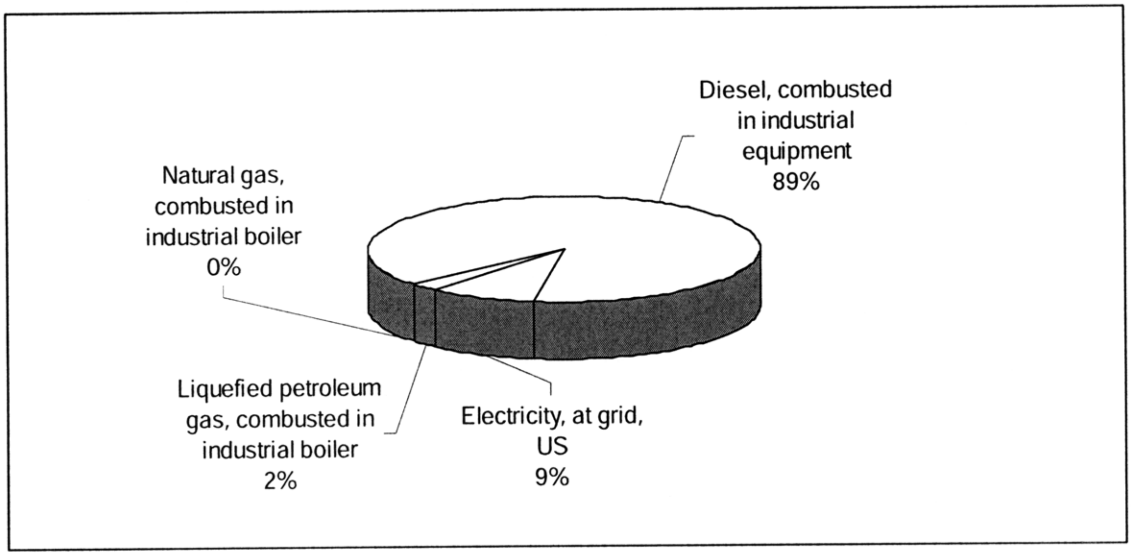

Figure 9: Energy input, by type, for cotton production.

The calculation of particulate emissions that result from burning a wick is highly sensitive to a number of factors that are impossibly to quantify generically. The "soot point" or rate of particulate production depends on the composition of kerosene, the length of wick burning or size of flame, and the material properties of the wick. In addition to the material composition of the wick, how tightly the fiber is spun and how it is twisted together – or plied – generates uncertainty for calculating the soot point[17]. As a result, the particulate emissions for wick combustion were determined from measurements taken on actual hurricane lamps by researchers from the Program on the Environment in Honolulu, Hawaii.

Wick consumption by kerosene lanterns was measured to be 2.5 grams per hour of burning. This allowed us to calculate the emissions for cotton production were calculated to be 200 times more significant by weight in wastewater disposal than in air emissions. Wick production only contributes to the critical pollutants shown first in Figure 4 in the form of particulate matter and nitrous oxides, some of which are dissolved solids rather than gases.

3 Solar Lanterns

Solar lanterns have been identified by a number of research and private organizations as a solution to the off-grid fuel-based lighting demand in developing countries. Without access to the electric grid, there are few solutions for clean, continuous power at an affordable and small scale. Alternatives include hand cranks and battery-powered torches and lanterns. These are often insufficient for lighting needs on a long term scale due to access to compatible equipment (replacement batteries, etc) and are also plagued by the "market spoilage" that occurs when dummy batteries are sold at exorbitant prices.

One private company entering the off-grid solar lighting space, Sollatek has developed the Glowstar lantern (Figure 10), a lower-cost alternative to a full solar-home-system that provides the most critical of electricity requirements in a developing world household. These lanterns are also marketed as an emergency light for consumers with access to the electric grid. The Glowstar comes in two size configurations, with solar modules of 5 watts and 10 watts. The 5-watt variety, designed specifically for developing world applications, have been the rough model on which the following life cycle calculation is based[18].

The biggest barrier to entry for solar lanterns is the investment required from the customer up front. Even the "low-cost" Glowstar lantern is priced at $100, which is ten times more expensive than the typical hurricane lamp[19]. Although there is no fuel requirement over its lifetime, it is very difficult for the poor to save and purchase an item so pricy. Forms of micro-financing, either by the solar company or through a third party, may be required for significant penetration of solar lanterns. In the meantime, it is important to recognize the energy requirement and environmental impact that widespread adoption of solar lanterns would have. The following life cycle assessment has been conducted to ascertain the impact, and compare it with the current impact of the same service provided by the conventional kerosene lamps.

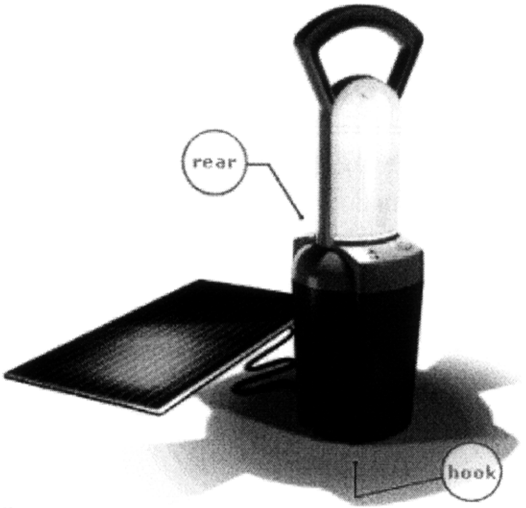

Figure 10: Artists rendition of Sollatek's Glowstar lantern.

Product Process Model

Functional Unit

For the solar lanterns, the functional unit will also be light providers for one family for 10 years. The two varieties of solar lantern that are discussed in this paper differ only in the light source itself: compact fluorescent light bulb (CFL) or light emitting diode (LED). While the lifetime of a solar lantern is shorter than that of a kerosene lamp – and thus requires multiple units over the time period – it should be noted that the light output of a solar lantern is superior. Thus, a comparison has also been made for emissions per lumen for each of the types of lamps. Unlike kerosene lamps, however, solar lanterns do not require a consumable fuel to operate; the sun's energy comes at no cost to the user and is outside the system boundaries.

System boundaries

As with the kerosene lamps, the solar lanterns will be evaluated "cradle-to-user".

Data quality requirement

As a first order discussion of the life cycles of kerosene lamps and solar lanterns, the data quality requirement is relatively low. In some cases, where data is not available for production mechanisms in the country of interest, United States data has been substituted. In the case of electricity fuel mix, US coal power plants have been used based on the assumption that most production would occur in China where the primary source of electricity is coal. Again, the questions are about scale and calculations will be consistent across comparisons so rough values are sufficient.

Critical review considerations

The following aspects will be taken into account as a second order evaluation: inflation of kerosene prices and discount rates on both the investment of the lamp and emissions over time. The same evaluation will be conducted for the solar lanterns with which these kerosene lamps are being compared.

Material and Energy Inputs

The lantern specifications for this life cycle analysis were based loosely on the technical specifications and requirements of the Sollatek Glowstar GS5. This is a 5-watt lantern that utilizes a rechargeable lead-acid battery. The running time from a full charge is 5.2 hours, which corresponds almost exactly with the lighting demands of rural Kenya. The time to charge is approximately 7 hours which is reasonable for daily recharge operation[20]. The limiting factor for the lanterns' life is the battery, which only operates at full capacity for about 500 charging cycles. The rest of the lamp has been designed to last about the same length of time, or approximately three years. This analysis has assumed that for 10 years, a household will need to purchase four solar lanterns (such that there are two in use at any given time).

	Frame	Battery	PV	Light Source
Specifications	2.4 kg, polypropylene	2.4 kg, lead acid battery	5-watt mono-crystalline	5-watt compact fluorescent
Raw Material Extraction	Yes	Yes	Yes	Yes
Component Manufacture	Yes	Yes	Yes	Yes
Component Assembly	Lack of Data, negligible	Yes	Yes	Yes
Transportation	n/a	n/a	n/a	n/a
Utilization	Yes	Yes	Yes	Yes
Recycling	No	No	No	No
Disposal	No	No	No	No

Table 3: Component data consideration for the following life cycle assessment\ of a solar lantern.

Due to the complexity of the components of a solar lantern, much of the following analysis is derived from previous studies. For example, the intricacies of photovoltaic (PV) manufacturing are well understood by experts, and energy payback times and emissions outputs have been quantified to a level of detail that is beyond the data quality requirement of this paper. The "black boxes" used in this analysis include the PV module that converts the sun's energy to electricity and the compact fluorescent light bulb that provides the light output to the user. They are described schematically in Figure 11.

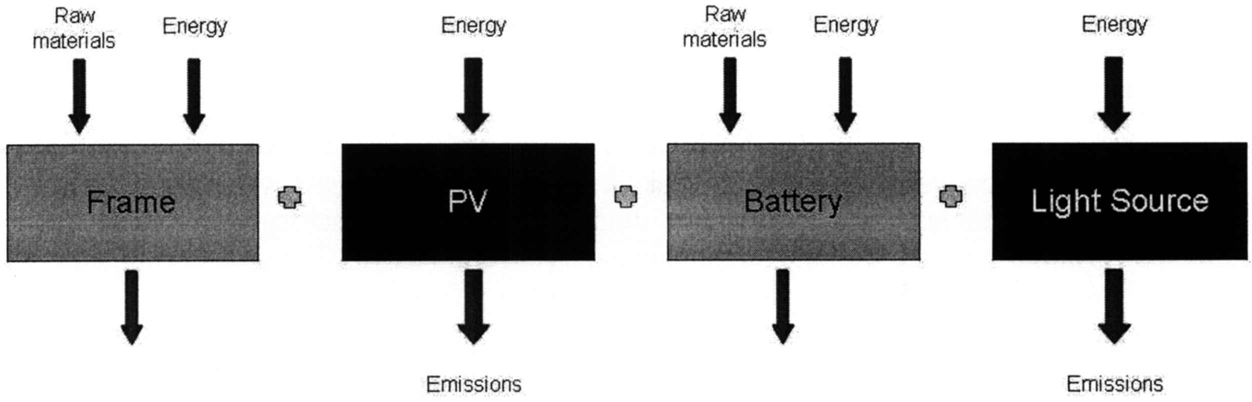

Figure 11: Schematic of solar lantern life cycle assessment.

Frame

Although we could not obtain confirmation from Sollatek, we have assumed that the composition of the lantern frame is made of injection molded polypropylene. This decision is based on a survey of solar lanterns available to consumers as well as the availability of reliable data[21]. One Glowstar 5S lantern weighs 2.4 kg, a value that we assume to include the frame, electronics, and light source, but not battery or photovoltaic module[b].

The energy input and energy related emissions data for raw material production of polypropylene and the subsequent formation of parts was obtained from an environmental analysis of injection molding conducted by Alexandre Thiriez and Timothy Gutowski of the Massachusetts Institute of Technology. The total energy input was calculated to be 244 MJ per lantern requirement and is broken down by process in Figure 12. The energy input and energy emissions related data is dependent on the type of injection molding utilized for production[22]. In the interest of conservatism, the most energy intensive – hydraulic injection molding – was assumed to be the case for these solar lanterns. On the other hand, the energy required for assembly of components was not available from Sollatek manufacturing data and was assumed to be negligible compared to the raw material production. Further revisions of this calculation should confirm the type of injection molding used and the impact of assembly in the energy input calculation.

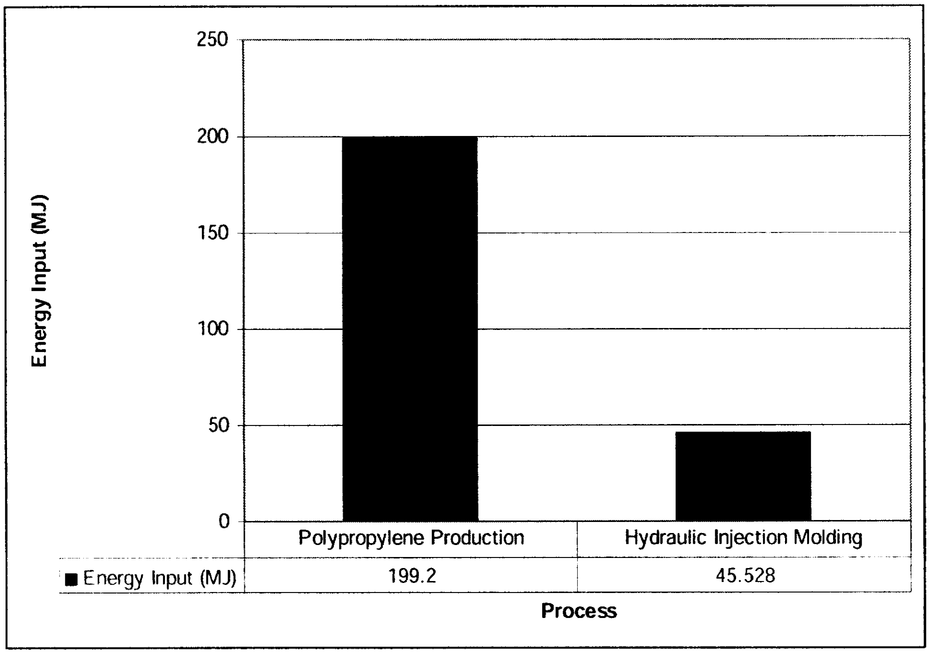

Figure 12: Energy input per solar lantern frame produced.

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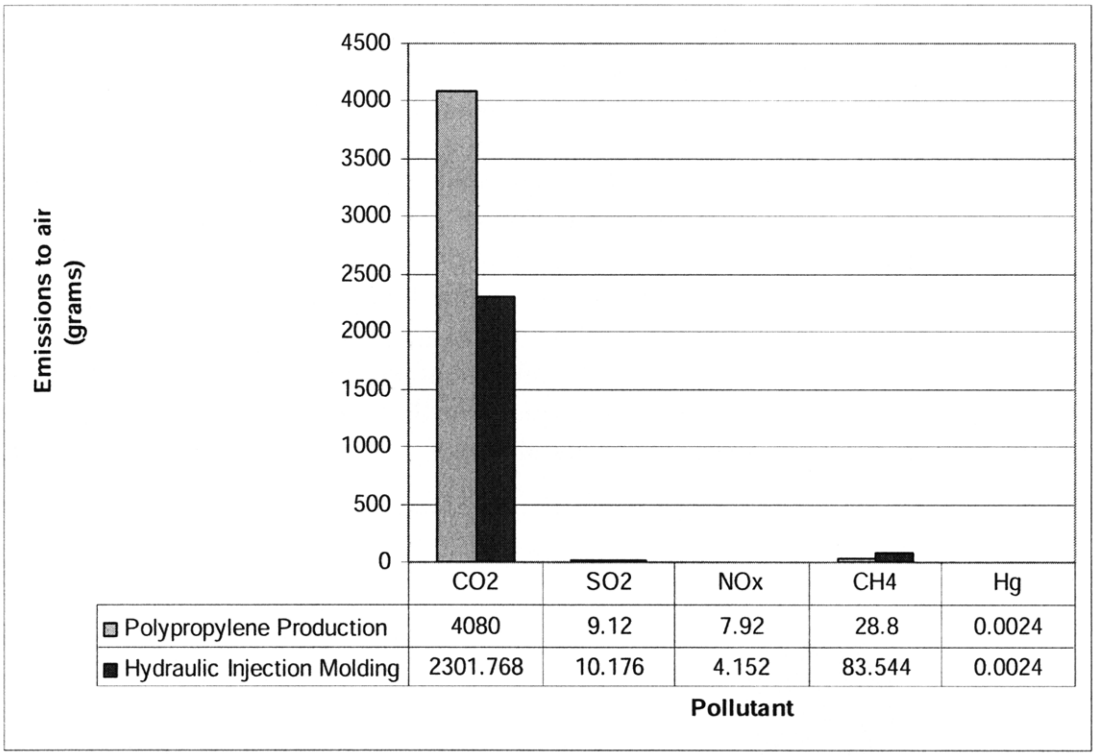
[b] The reason for this assumption is the following: Sollatek sells the solar module part separately from the lantern, and our calculations indicate that a lead-acid battery of weight 2.36 kg is required to meet the energy demand of the lantern. It would not be reasonable to assume that only 0.04 kg of the lantern compromise the remaining components.

The MIT study references a report prepared by Ian Boustead for Plastics*Europe*, that details the emissions from the production of polypropylene[23]. Added to the emissions reported for energy use in injection modling we found that emissions to air are 1000 times that of water and 70 times that of solid waste and are thus considered to be the most significant. They are depicted, by critical pollutant, in Figure 13.



	CO2	SO2	NOx	CH4	Hg
▨ Polypropylene Production	4080	9.12	7.92	28.8	0.0024
■ Hydraulic Injection Molding	2301.768	10.176	4.152	83.544	0.0024

Figure 13: Emissions to air per solar lantern frame produced.

Battery

Sollatek uses lead-acid batteries in their Glowstar lanterns. The batteries are 4.4 Amp-hour batteries with a nominal voltage of 12 Volts. The maximum charge current is 0.6 Amps and the running time from a full charge is 5.2 hours. The power required for a GS5 lantern is calculated from Equation 2, where P is the power required, β is the battery capacity, t is the running time from full charge, and V is the nominal output voltage.

$$\mathrm{P} = \frac{\beta}{t} \cdot V \cdot t$$

Equation 2: Power requirement for solar lantern.

The mass of the lead-acid battery was then calculated from Equation 3, where M is the mass required, P is the power requirement (or the discharge per cycle), η_{cd} is the charge-discharge efficiency, d is the depth of discharge, and ρ_{energy} is the energy density of a typical lead-acid battery.

$$M = \frac{D}{\eta_{cd} \cdot d \cdot \rho_{energy}}$$

Equation 3: Mass of lead-acid battery.

The weight calculated for the lead-acid battery component of a solar lantern is 2.36 kg. This value was used for all subsequent calculations.

The bill of materials for a lead-acid battery is shown below[24]. We considered only the energy input and emissions for the raw material production of lead, polyethylene, and polypropylene, assuming that for all others, the production is either very small or that the material is required in such a small quantity that it is negligible in the process.

Material	per kg battery
Antimony	0.71
Arsenic	0.03
Copper	0.01
Glass	0.2
Lead	60.96
Oxygen	2.26
Polyethylene	1.83
Polypropylene	6.72
Sulfuric acid	10.33
Water	16.93

Table 4: Bill of materials for lead-acid battery production.

The total energy input, derived from the raw material production data for lead[25], polyethylene and polypropylene, plus energy for manufacturing[26] is described in Figure 14.

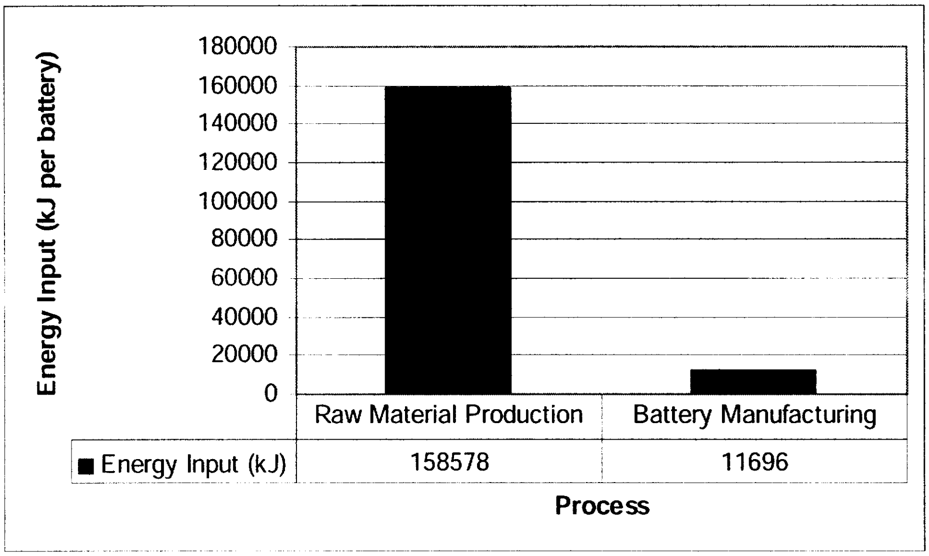


Figure 14: Energy input per battery required for a solar lantern.

Emissions data was derived from the raw material production processes and the emissions that result from the fuel mix of electricity and combustion of oil and liquid propane gas used for manufacturing. The totals for each critical pollutant are shown in the following figure.

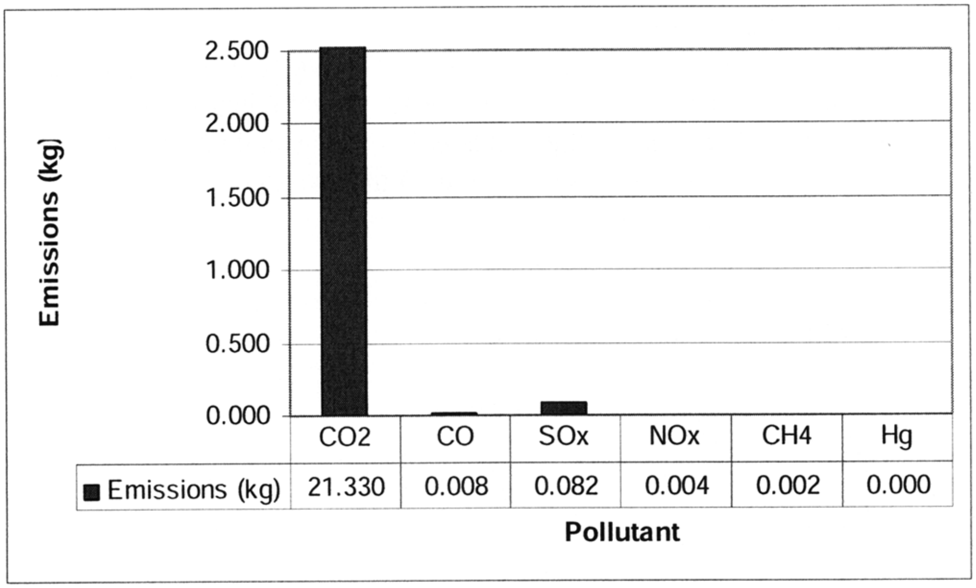


Figure 15: Emissions per battery required for a solar lantern.

PV Module

The photovoltaic module "black box" was modeled from energy input data presented by Erik A. Alsema and Mariska J. Wild-Scholten[27]. The total energy input is 41 MJ/Watt-peak of PV panel produced. This corresponds to 205 MJ for the 5-Watt module used in a Sollatek lantern. The energy requirement for production is detailed by production process in Figure 16.

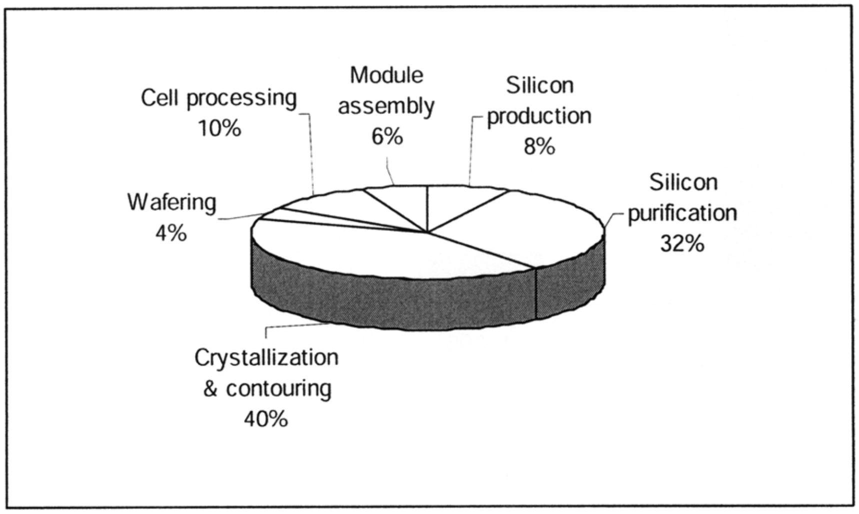


Figure 16: Energy input, by process, for mono-silicon photovoltaic production.

The data for emissions for photovoltaic life cycles is reported by Vasilis M. Fthenakis, in collaboration with Mr. Alsema, which indicates relatively consistent data across studies[28]. They found the following emissions in milligrams per kilowatt-hour (kWh) of electricity eventually produced by the panel for the designated critical pollutants[c].

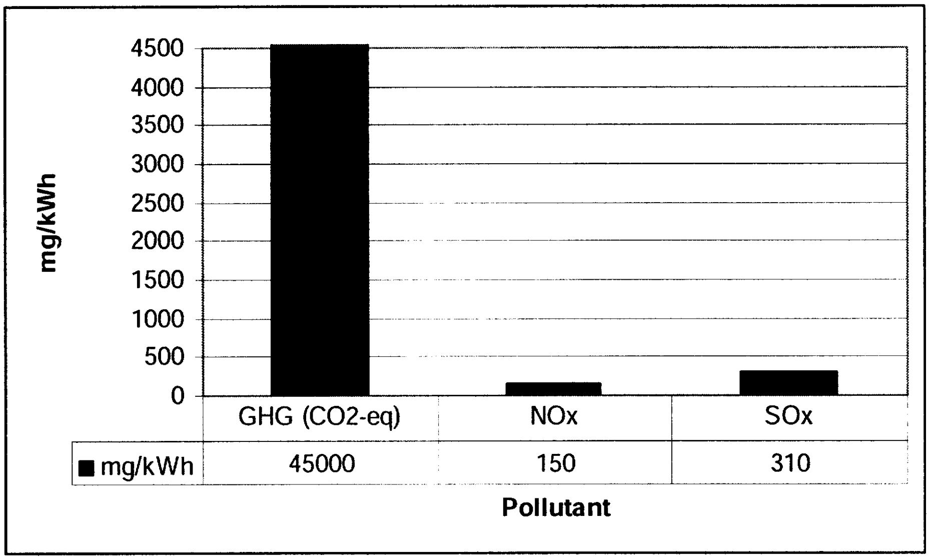


Figure 17: Emissions from the life cycle of a photovoltaic panel, normalized by kWh produced.

Lamp

Solar lanterns typically use compact fluorescent light bulbs (CFLs), but are starting to implement solid state light emitting diodes (LEDs) as well. First, we compared life cycle analysis for energy input, or consumption, over the lifetime of each bulb. The comparison is made based on a light output rating of 16000 lumens – for which a CFL requires 23 watts of power input and an LED requires 20 watts. The data for the CFL was derived from a study conducted by Anette Gyesden and Dorte Maimann[29], while the LED life cycle estimation is a preliminary figure from Professor Matthews of Carnegie Mellon University[30]. The graph below shows the standard life cycle data for energy consumption of the two kinds of light bulbs. The emissions for each would be estimated based on the electricity consumption of each bulb's life cycle and would easily be derived from the emission factors of an average grid mix.

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[c] CO_2 equivalence is calculated based on the global warming potential of other greenhouse gases, specifically methane (or CH_4). The International Panel on Climate Change (IPCC) has designated that, on a 20-year scale, and normalized to CO_2's potential the global warming potential of CH_4 is a factor of 72.

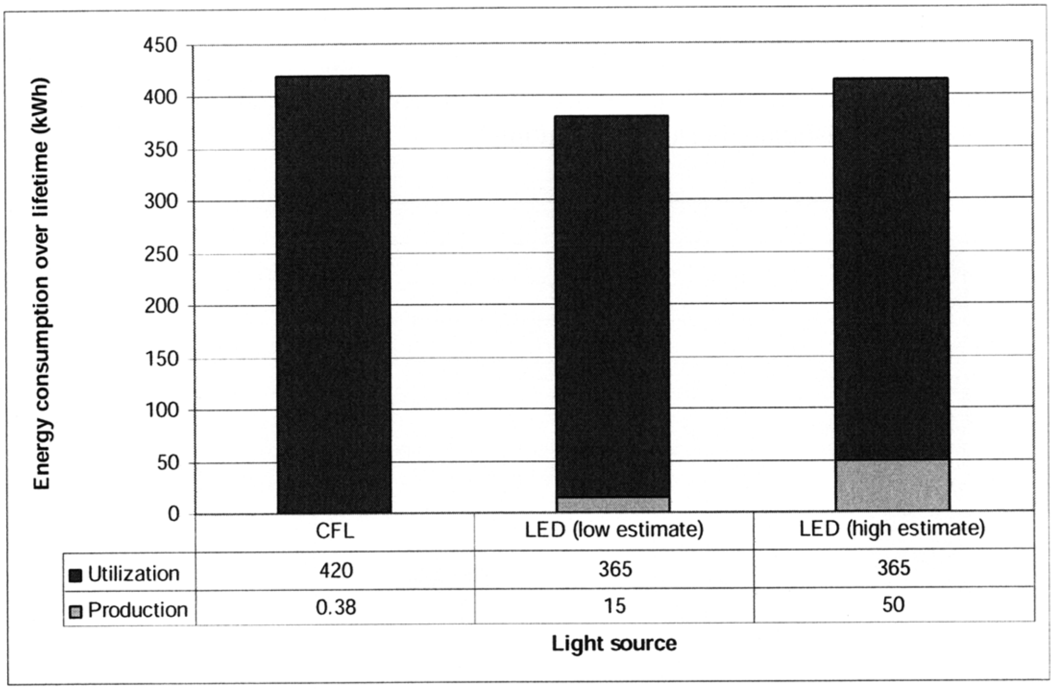


Figure 18: Comparison of life cycle energy consumption of a compact fluorescent light bulb (CFL) and a solid state light emitting diode (LED).

The benefit of LED lighting options is the reduction in power requirement during the utilization phase. Since the electricity provided is fixed at the 5 watts provided by the designated solar module, a solar-powered LED does not see this benefit. However, an LED of a given watt-rating will have a greater lumen output than an equivalent CFL by about 13 lumens per watt.

CFLs have the same benefit with respect to the conventional incandescent bulbs. The Gyseden and Martin study indicates estimates that the production of a 15-watt compact fluorescent bulb that provides 7.2 million lumen-hours requires 1.4 kWh while the production of a 60-watt incandescent bulb that provides 0.73 million lumen-hours requires 0.15 kWh. A major benefit to CFLs is the lifetime of the bulb; when normalized by lumen-hour, an incandescent requires twice as much energy to produce. An LED typically operates for 2.5 as long as a CFL.

In the case of the solar lantern, the electricity of utilization is provided by the sun and is therefore not relevant to emissions. Thus the LED surpasses the CFL in emissions per lumen as shown in Table 5 below.

	CO2	CO	SOx	CH4	NOx	Particulates	**Total**
CFL	1.11E-03	3.53E-07	3.60E-05	2.84E-09	1.82E-06	1.04E-08	**1.15E-03**
LED (average)	3.29E+01	2.54E-05	2.59E-03	5.56E-06	1.31E-04	7.52E-07	**3.29E+01**

Table 5: Critical pollutant emissions normalized by lumen for CFL and LED in kilograms per lumen.

The CFL was chosen to be integrated in the life cycle analysis of a solar lantern because it is the standard technology used in Sollatek's Glowstar lanterns. It also represents the median technology in terms of both consumption and performance.

4

Life Cycle Analysis Results

After tabulating and summing all life cycle processes for each component of each lighting option, the following results were obtained. The total energy input for the hurricane lamp is about 2 times that of the solar lantern, while the energy input for the solar lantern are twice that of the tin lamp. Because of the definition of the functional unit – 10 years of lighting at 5 hours per day – four units of solar lantern were considered for the same period of time that two (of either) kerosene lamps may be used. The total life cycle sums are shown in the following figures. It is important to recognize that the order of magnitude of each comparison, and realize that, due to uncertainty in the data available, the exact values may change in future revisions.

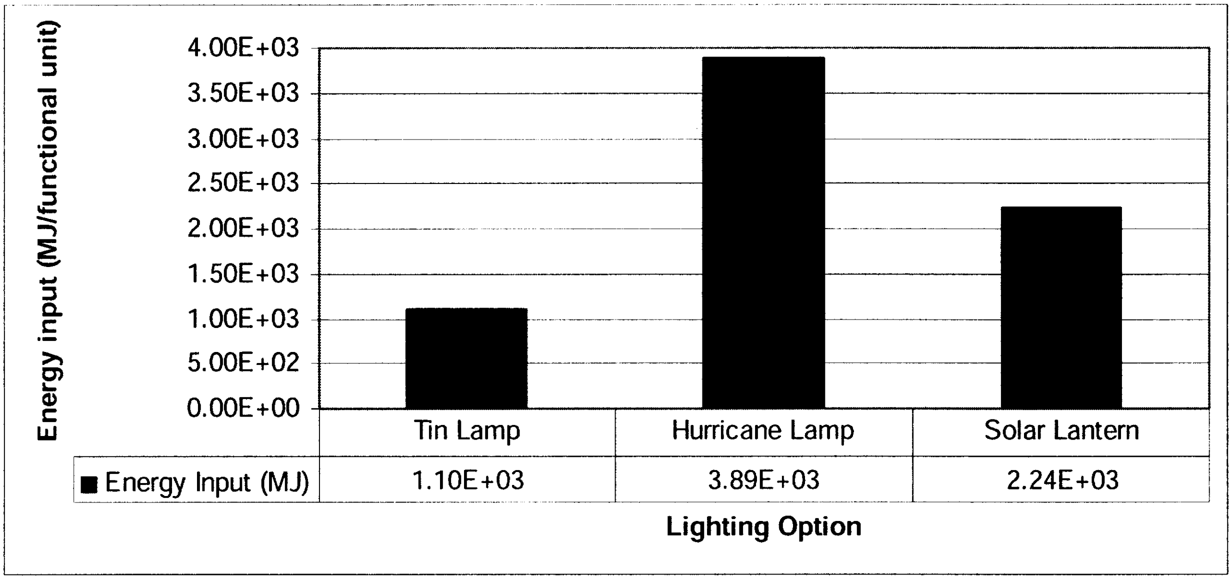
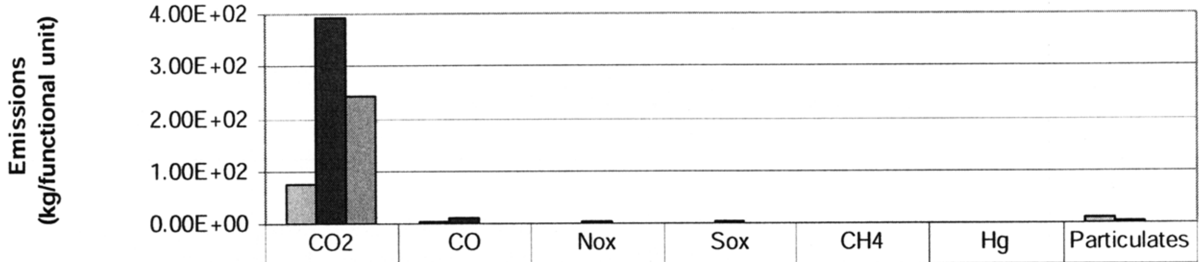


Figure 19: Life cycle energy input for 10 years of lighting options.



	CO2	CO	Nox	Sox	CH4	Hg	Particulates
□ Tin Lamp	7.39E+01	1.94E+00	1.39E+00	3.39E-01	1.59E-02	5.55E-09	9.76E+00
■ Hurricane Lamp	3.92E+02	1.02E+01	3.39E+00	1.83E+00	8.34E-02	7.21E-08	4.53E+00
▨ Solar Lantern	2.43E+02	7.70E-02	1.44E-01	1.01E+00	4.70E-01	1.97E-05	1.57E-03

Figure 20: Emissions in kilogram per functional unit for the life cycles of kerosene lamps and solar lanterns.

The hurricane lamp has the greatest impact in terms of emissions. It is interesting to note that the production of kerosene accounts for 99.6% of the greenhouse gas (CO_2-equivalent) impact of the entire hurricane lamp life cycle. However, the particulate emissions are greater for the simple tin lamp than the hurricane – and significantly greater than that of the solar lantern – nearly all of which occurs during combustion in the home. When normalized by lumen, the emissions intensity from a solar lantern is 160 and 9 times better than from a tin lamp and hurricane lamp, respectively.

Uncertainty in results

These results, while relevant for comparison, contain a degree of uncertainty. As descried in the previous section, there are many underlying assumptions that were required to quantify each step of the process. Average values were used where possible, but the data quality requirement was low and so the analysis will not be exact for any given situation. Propagation of uncertainty was not carried out for these first-order calculations, but as more specific data becomes available, it will become essential.

Nevertheless, the results are valuable for comparisons sake. Order of magnitude estimates facilitate discussion and determine where to focus efforts for the next level of precision. Those are among the intents of presenting the quantitative results of this study.

5 Conclusions

Having evaluated the life cycle input and emissions of kerosene and solar lanterns, it appears that there is not an obvious benefit to solar lanterns based on the lifetime energy input and emissions release. Additional factors, including which type of kerosene lamp that a solar lantern would replace, must be considered in a decision to transition to solar-based lighting. The cost of a solar lantern is about ten times that of the more expensive hurricane lamp and one hundred times that of a locally made tin lamp. Further, solar lanterns last only three to four years and thus four were required to match the lighting requirements of two kerosene lamps in this study. While total pollution emissions are of the same order of magnitude, the distribution of the emissions is vastly different. Solar lanterns eliminate particulate pollution within the home, while kerosene lamps emit the majority of the particulate emissions only in the home, causing health issues for their users. In addition, solar lanterns may create a new industry of photovoltaic and battery production, but eliminate the local employment of tin lamp manufacture.

In order to further determine the costs and benefits of replacing fuel-based kerosene lighting with solar lanterns, these impact considerations must be discussed. With more conclusive field research for lighting requirements and value placed on a local tin lamp-making industry, a sustainable and effective transition may be achieved.

Economic payback

Although the cost of one Sollatek Glowstar GS is $100, ten times that of the hurricane lamp, the economic payback time indicates that it is a reasonable investment. A household using a hurricane lantern for five hours per day will spend about $90 per year on kerosene. Adding the $10 cost of the hurricane lamp, this means that the payback time of a solar lantern is effectively one year.

The difference is that the cost of the solar lantern is one lump sum, while consumers can buy kerosene in very small quantities, depending on their income level in a given week. Kerosene is consumed in a hurricane lamp at approximately 1.5 litres per week, but is often purchased in amounts less than 0.5 litres (38 Kenyan Shillings, or $0.57) at a time. The *structure* of purchase is different, and is thus more desirable to the poor.

A net present value (NPV) can be calculated for each lighting option to examine the economic impact over ten years. For two hurricane lanterns and the fuel associated with five hours of lighting per day, the NPV of the cash flow pay outs is about -$165 over ten years, with a total sum of $1,965 in costs. This assumes that ten years consists of 120 pay periods, and that household purchases enough kerosene each month to last until the next time of purchase. If four solar lanterns are purchased in a lump sum at distributed times such that there are two lamps in use at all times after the first six months, and assuming that a household can save appropriately, the NPV of the cash payout is about -$147, with a total sum of $400. The discount rate assumed in both cases is 10%. The fact that the two NPVs are so similar shows how deferring the cost of lighting the form of fuel purchase is equally desirable to paying an $1,500 less in total, rather than lump sums of $100 payments[d].

Microfinance exists in developing countries to help reduce the impact of lump sum purchases of durable goods that may improve overall standard of living. In very low-income situations, it is nearly impossible for families to save, making a purchase like that of a solar lantern seem entirely unaffordable. Various forms of microfinancing are in use in regions like Sub-Saharan Africa and rural India. In some cases, lenders may offer money to families who wish to purchase a solar lantern. The family would then pay the lender back over a period of time, say two years, at a low level interest rate. (This family would not have been able to borrow from a bank because of lack of assets for collateral on the loan. In addition, banks are rarely willing to lend just $100 at a time.) In another form of microfinancing, a family would continue to "deposit" money to a person, usually a local with a good reputation, who would manage the risk of the loan he or she could subsequently make. When the family has deposited enough money, it can then withdraw the full amount to purchase their lantern. These approaches have been used successfully for various purchases of durable goods such as cooking stoves, television sets, or cell phones, and are an appropriate tool for implementation of solar lanterns.

Assuming each solar lantern is paid for installments of $6.00 per month and a 30% interest rate is applied to the total sum at the end of ten years, the cash payout NPV of the same scenario is only -$60, with the total money spent being $522. This scenario, if the institutions exist to support it, is economically desirable to consumers independent of the quality of light or environmental benefits which they are also receiving.

The same calculation may be conducted for the simple wick "tin" lamp, which costs the user $1 equivalent to purchase, and about $17 to fuel for one year. The total spent over ten years is just $171, and the NPV of the investment is -$16. This is a significantly cheaper option and probably cannot compete with the Glowstar G5 in its current form even with an extreme financing mechanism.

However, it is critical to recognize the additional costs that are associated with fuel-based kerosene lighting. Economically, the price of kerosene is not fixed for the next ten years (although it was assumed to be in the above net present value calculations). While the cost of kerosene to the customer may not exactly reflect the price of crude oil, as resources are diminished and richer countries become willing to pay more for the fossil fuel resource, kerosene is likely to become unaffordable for very poor people. There is a risk associated with being entirely dependent on a fuel whose price is volatile.

In addition, health issues related to indoor air quality are difficult to quantify in monetary terms, but are of a serious nature and discussed in the next section. Babies are especially susceptible to deaths related to polluted air, and the most educated – or those who study by kerosene lamps the most – will be the most affected in their society. Further, while it is impossible to enforce a price for carbon in the unregulated markets of Sub-Saharan Africa or rural India, the environmental cost of kerosene production and use of fossil fuel resources is one that society does have to bear. Finally, the quality of light provided by a solar lantern is far superior to the flickering, dim, and diffuse light produced by kerosene combustion. Direct and brighter lighting improves productivity within the home, both for money-making activities and education, thereby enhancing the overall quality of life for the household.

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[d] Because the net present value (NPV) is being calculated for a pay out, rather than the standard cash flow in, the most desirable NPV is the *least negative*. An NPV that is closer to zero means that the pay out is less, and therefore more desirable.

Impact of Emissions

The results of this study also indicate that solar lanterns displace emissions from the end-user's home to a more centralized manufacturing facility. Even if the quantity of emissions is equivalent for the life cycle of a solar lantern, it is still arguably more desirable due to the location distribution. In terms of total emissions, the hurricane lamp emits the most while the tin lamp emits the least. The tin lamp, however, emits the most particulate matter inside a home, which has the greatest directly negative impacts on the user. Switching from a $1 tin lamp to a hurricane lamp that is ten times as expensive reduces particulate emissions by the equivalent of 10-15 cigarettes per hour. Switching to a solar lantern, ten times as expensive as a kerosene lamp, completely eliminates indoor air pollution due to lighting.

Health effects are not directly due to ambient concentrations, they are correlated with doses, which refer to the air actually breathed by people[31]. Negative health impacts include severe asthma, lung contamination, and increased spread of infectious diseases. These can be fatal to the most sensitive – babies and the elderly – and will have the greatest long-term impact on family members who engage in education and require the light to study by. Due to the location distribution of particulate emissions, the impact of replacing kerosene lamps with solar lanterns is greater than the absolute value of total emission comparison would suggest.

For the solar lantern, one concern with using CFLs is the hazardous waste disposal due to the 5 milligrams of mercury in the composition of one bulb. Mercury, while present in very small quantities in a single bulb, is a heavy metal that is toxic to humans in the case of exposure and is difficult to remove once deposited in the ecosystem. Members of the food chain accumulate mercury through ingestion, and by the time a human eats a contaminated food, mercury could exist at dangerous levels. Research must be conducted on the nature of treatment of a household toxic substance in developing countries where the poverty level is high and the education rate is low. Meanwhile, one CFL will also provide light for 10,000 hours, which translates to 5.5 years at the rate of lighting use that occurs in fuel-based lit homes today.

Although the typical kerosene lamp user will not think of emissions in terms of a discount rate, it is a useful metric for comparison. A solar lantern experiences all of its energy inputs and emissions release in the production of the product, but operates independently and cleanly for its life cycle. Meanwhile a kerosene lantern experiences its emissions distributed by consumption over the course of its life. When an 8% discount rate is applied to the emissions – assuming that the value placed on emitting in the future versus now is lower than paying money in the future versus now – the net present value calculation for emissions results in 167 kilograms and 233 kilograms for hurricane kerosene and solar lighting respectively[e]. This means that although the kerosene lantern emits more over its life cycle, deferring the pollution to the future (and perhaps the impact to future generations) is preferable over the time scale. This calculation may substantiate an argument against solar lanterns as a "clean source" of lighting.

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[e] In this case, the desired NPV is also as close to zero as possible, because that means the least amount of pollutants are being released (unlike the NPV for positive cash flows where the greatest positive cash flow is desired).

Impact of Scale

Introduction of a new technology often appears feasible and beneficial on a small scale and when evaluated independently. However, for the impact to be recognized socially, solar lanterns must replace kerosene lamps *at scale*. This will result in a significant shift in industry demand requirements, and must be considered for successful implementation.

Silicon Demand

For the photovoltaic industry, silicon is the limiting factor for PV manufacturing in terms of cost and availability. The cost of production of solar modules is dependent on the market price for silicon, and the modules with the least amount of silicon per watt-peak are the most desirable for their independence from the secondary market. Silicon demand globally is projected to be about 100,000 tonnes per year in 2010[32]. The silicon required if every single kerosene lamp in India were replaced with a solar lamp would be about 2000 tonnes, or just under 2% of the annual silicon supply[33]. Although it is also impossible to penetrate the fuel-based lighting market at such high level, this value provides some means for comparison. As shown in the figure below, if 10% of kerosene lanterns in India were replaced by solar lanterns, the silicon required would compromise 0.20% of the annual global supply.

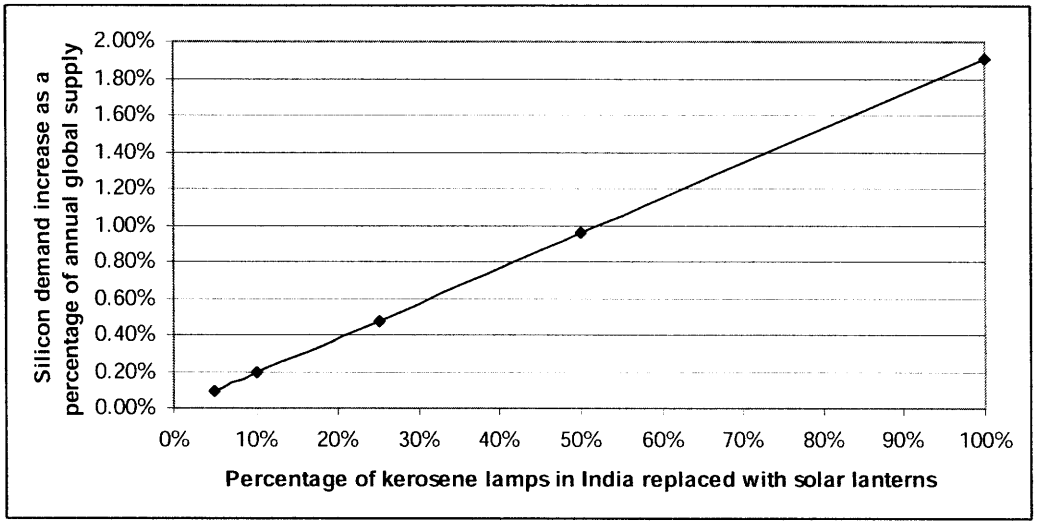

Figure 21: Silicon demand increases as a percentage of annual global supply with respect to fuel-based lighting market penetration.

Battery Disposal Waste

For each kilogram of battery waste, there are 0.61 kilograms of lead that must be disposed of correctly. In the United States this presents an issue, as heavy metals are likely to be sent to landfills, and would thus enter the biosphere. However, in countries such as India, there exists an extreme, effective form of recycling.

Due to the vast differences in the economic ladder, there are always people poor enough to need to scavenge and sell parts in order to generate income. Valuable substances such as heavy metals are sought after by unemployed members of society, attempting to generate even just a little income. While the institution of recycling may not exist in a formalized manner, the likelihood of any substance with a monetary value ending up in solid waste disposal landfills is smaller than in richer countries. Although this analysis did not quantify the cost of disposal in energy and emissions, it should be understood that near-zero emission recycling is a viable, and probable, result.

Future Considerations

One option that would address both energy input and emissions release, and cost would be reducing the specifications of a solar lantern. At present, the Glowstar G5 provides 350 lumens; compared to the 7.8 lumens from the typical tin lamp and 67 from a hurricane lamp, a solar lantern emits 45 and 5 times more light. Thus, when energy and emission intensities are normalized by lumen, the impact is far less than for the kerosene lamps. If a solar lantern were designed to specifications of only 100 lumens – with a 1.5-watt compact fluorescent light bulb – the total impact may scale down as well, if not linearly then at some proportional rate.

Field research must be conducted to determine whether users of kerosene lamps require or desire more lumens in their home, and at what price they value an increased amount of light. With these results, it would be possible to design a lantern that is optimized for consumer requirements but still exhibits an environmental benefit. Data suggests that the light that kerosene lamps provide results in an unsatisfied demand – both in quality (lumens) and in quantity (hours). When solar lanterns of similar specifications to the one discussed in this study were introduced at no cost to the user to villages in rural India, the observed reduction in kerosene consumption was only 50% what should have been displaced. This so-called rebound effect indicates that the total effect was net positive consumption; users simply used their solar lanterns in addition to some of their existing kerosene lamps[34]. The question is, then, whether solar lanterns should aim to simply displace total impact or to improve upon the net negative saving that would currently occur.

6 Recommendations

While everything in this paper has been calculated to the level of precision of data available to the author, this study is simply a first-order, first-pass life cycle analysis calculation. A review should be conducted on each of the life cycle analyses used within this report to ensure that system boundaries are as consistent as possible, preferably with confirmation of the authors of the papers from which data was derived.

To make the study more accurate, the most recent data possible should be used. For example, photovoltaic manufacturing processes have increased in efficiency of operation, but the most recent LCA data available is from 2004. With increased production, economies of scale, and improvements in manufacturing technology, it is possible that the environmental impact of the solar lantern will decrease further. In addition, data should be obtained for the actual manufacture of lanterns, rather than industry averages of processes. Different suppliers of lanterns will provide different values, and an individual LCA balance should be calculated for each.

Just as LED technology is beginning to penetrate the lighting market, lithium-ion and other forms of rechargeable batteries are replacing lead-acid batteries in some applications. A cost-benefit analysis should be conducted first, followed by a life cycle assessment (there is little available life cycle data for lithium ion batteries) for the solar lantern application. These types of comparisons will allow for technology to be developed that has the greatest positive environmental impact while achieving the original goal of replacing fuel-based lighting with a generally more sustainable option.

Finally, even a decisive life cycle assessment will not provide all answers to a question of technology implementation. Social, economic, and political challenges may still exist even if a purely technological solution is discovered. An LCA will contribute to a better understanding of these issues, especially ones associated with environmental externalities, but must always be considered with respect to the scenario being analyzed. The results presented here provide the basis for understanding the potential for replacing fuel-based kerosene lamps with solar lanterns and should influence decisions made regarding future studies and investments.

7

Citations

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