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Technical Report #9

Embodied Energy and Off-Grid Lighting

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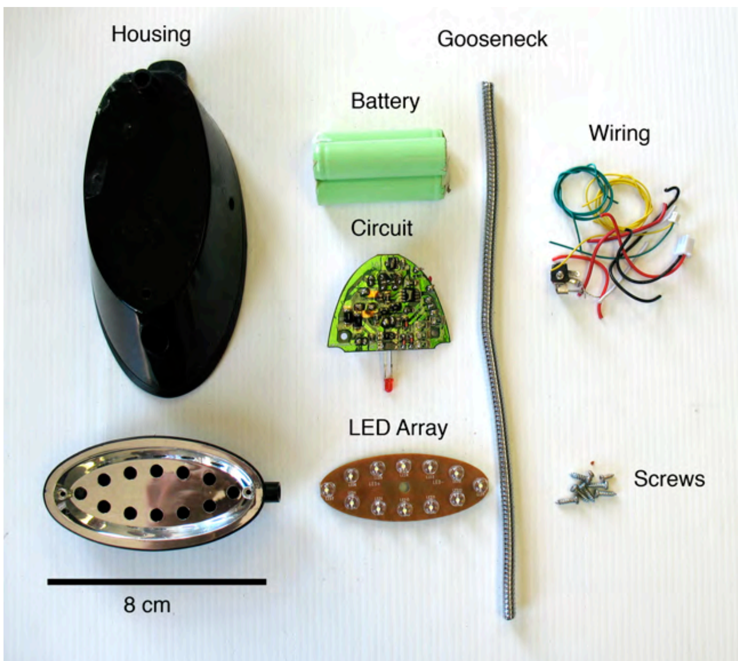

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The Lumina Project includes an Off-Grid Lighting Technology Assessment activity to provide manufacturers, re-sellers, program managers, and policymakers with information to help ensure the delivery of products that maximize consumer acceptance and the market success of off-grid lighting solutions for the developing world. Periodic *Research Notes* present new results in a timely fashion between the issuance of more formal and lengthy *Technical Reports*. Our results should not be construed as product endorsements by the authors or sponsors. For a full archive of publications, see: http://light.lbl.gov/technology-assessment.html

Summary

The greenhouse gas (GHG) emissions from fuel-based lighting are substantial given the paltry levels of lighting service provided to users, leading to a great opportunity for GHG mitigation by encouraging the switch from fuel-based to rechargeable LED lighting. However, as with most new energy technology, switching to efficient lighting requires an up-front investment of energy (and GHGs) embedded in the manufacture of replacement components. We studied a population of off-grid lighting users in 2008-2009 in Kenya who were given the opportunity to adopt LED lighting. Based on their use patterns with the LED lights and the levels of kerosene offset we observed, we found that the embodied energy of the LED lamp was "paid for" in only one month for grid charged products and two months for solar charged products. Furthermore, the energy-return-on investment-ratio (energy produced or offset over the product's service life divided by energy embedded) for off-grid LED lighting ranges from 12 to 24, which is on par with on-grid solar and large-scale wind energy. We also found that the energy embodied in the manufacture of a typical hurricane lantern is about one-half to one-sixth of that embodied in the particular LED lights that we evaluated, indicating that the energy payback time would be moderately faster if LEDs ultimately displace the production of kerosene lanterns. As LED products improve, we anticipate longer service lives and more successful displacement of kerosene lighting, both of which will speed the already rapid recovery of embodied energy in these products. Our study provides a detailed appendix with embodied energy values for a variety of components used to construct off-grid LED lighting, which can be used to analyze other products.

Introduction

It can be appropriately asked whether the energy embodied in the manufacture of any "green" energy technology is fully recovered over its useful lifetime. Analyses of embodied energy are well established, but only a few limited studies exist for emerging off-grid LED lighting systems that can be used to displace fuel-based lighting in the developing world.

The baseline greenhouse gas (GHG) emissions from fuel-based lighting are substantial, particularly given the negligible lighting services provided to users. This situation underpins opportunities for reducing GHG emissions by substituting fuel-based lighting with rechargeable LED lighting technologies (Mills 2005).

Energy Payback Period

The energy payback period of any energy technology intervention is generally equal to the amount of time it takes to offset the "embodied" primary energy that was required to manufacture, transport, and install the new technology. Estimates of embodied energy can be highly uncertain and depend strongly on the system boundary (Hammond and Jones 2008). In this report, our target boundary is "cradle to consumer," meaning that we include raw material procurement and processing, intermediate transportation, manufacturing, packaging, transportation, warehousing, and distribution energy. Note, however, that we do not include end-of-life energy requirements (which are minimal given the relatively low levels of waste management in many developing countries) or potential recycling/re-use of the materials.

Calculating embodied energy tends to follow one of two models: econometric input/output models (e.g., see Green Design Institute 2011) and material processing models (e.g., see Duque Ciceri et al. 2010). Econometric models for estimating embodied energy are based on typical economic energy intensities (e.g., MJ/$) for the industry that manufactures each component or system. Material processing models use a bottom-up accounting process to estimate the primary energy requirements based on physical quantities for each part (e.g., MJ/Watt for a solar cell) and process (e.g. MJ/kg for injection molding). In this report, we are strictly using material processing to estimate embodied energy.

Both econometric and material processing models have been used by others to estimate the embodied energy in improved off-grid lighting products. Donohoe and Boddy (2009) used a combination of econometric and material processing methods to estimate the primary energy requirement for a solar-LED-NiMH light for comparison to kerosene "wick" lamps (see Radecsky et al., 2008 for wick lamp description) and candles. Their estimate for the embodied energy of manufacture for an LED lamp powered by a ¼ watt solar module was 30 MJ; their estimate for the embodied energy of a kerosene wick lamp was 1 MJ. In another report, the author compared a much larger 2.5 W CFL solar lantern to both hurricane and tin lamps. That study includes an estimate for "cradle to user" energy requirements of 560 MJ for the solar lantern (Dave 2009).

Our analysis differs from and improves on past work by using a rigorous materials processing estimate of embodied energy for a product we have experience with in the lab and the field. We feel that econometric estimates for a specific product are likely to be inaccurate compared to materials processing methods because of the gross nature of industry-wide economic energy intensity estimates. Our field experience provides realistic estimates of kerosene offset as a point of comparison with LED lighting product embodied energy.

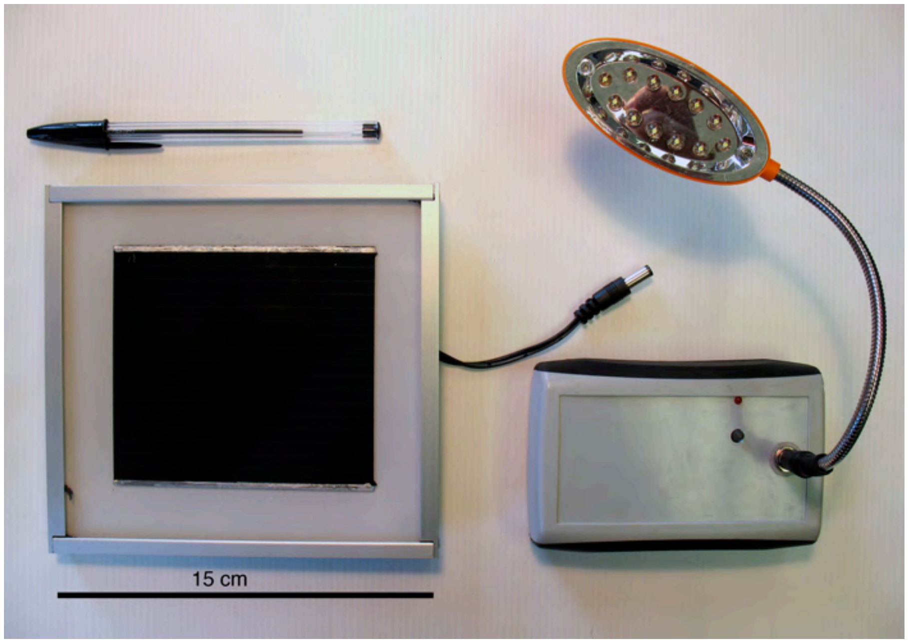
Solar LED Task Light Embodied Energy

We estimated the embodied primary energy in each of the two lamp options we offered in a recent market test—solar and grid charged—for comparison to the amount of kerosene that was offset by their adoption (Radecsky et al. 2008; Johnstone et al., 2009).

The lamp we offered in the study (pictured in figure 1a below) was based on a commercially available LED task light (pictured in figure 1b below) and included the same main components in addition to custom data logging circuits (the reason for the custom chassis). Our embodied primary energy estimates are based on the commercially available version; we assume that the kerosene offset by it would be the same as by the modified unit we offered for sale.

The method we used to estimate embodied energy was to break down the lamp, solar module, and grid recharger into their constituent components, measure the quantity of each component, and account for production processes. The broken down lamp and grid recharging circuit are shown in figure 2. We used publicly available embodied energy data[1] to account for the energy contribution of each component and process. The full dataset on embodied energy we compiled is available in Appendix 1; it is tailored for off-grid lighting product embodied energy estimates.

[1] Many embodied energy estimates (see Alsema and de Wild-Scholten 2006, Raugei et al. 2007, and many others) are based on primary energy intensity data from proprietary databases. In the spirit of Duque Ciceri et al. (2010) part of the goal of this analysis is to provide a freely available resource for others to estimate the embodied energy in off-grid lighting products.



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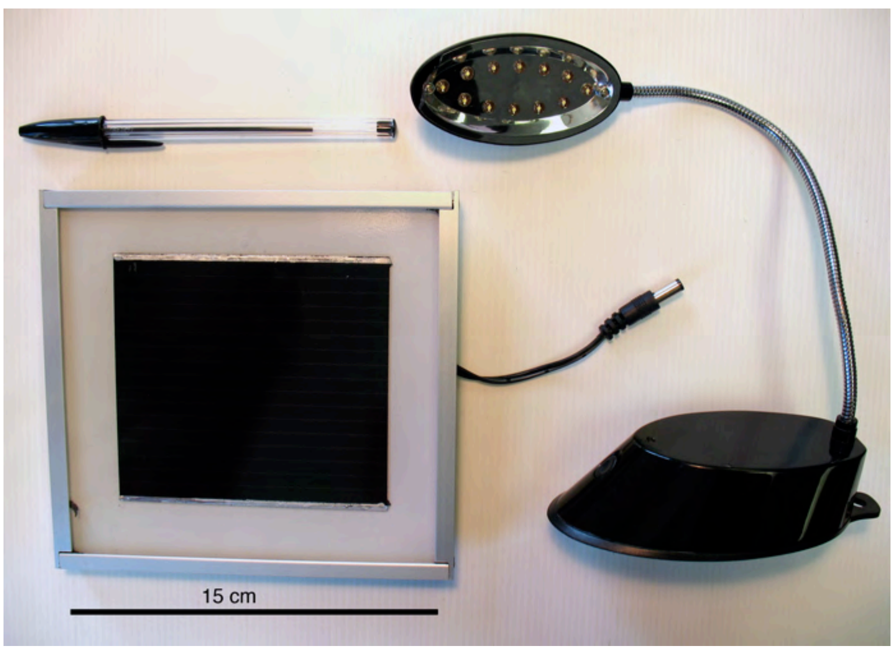
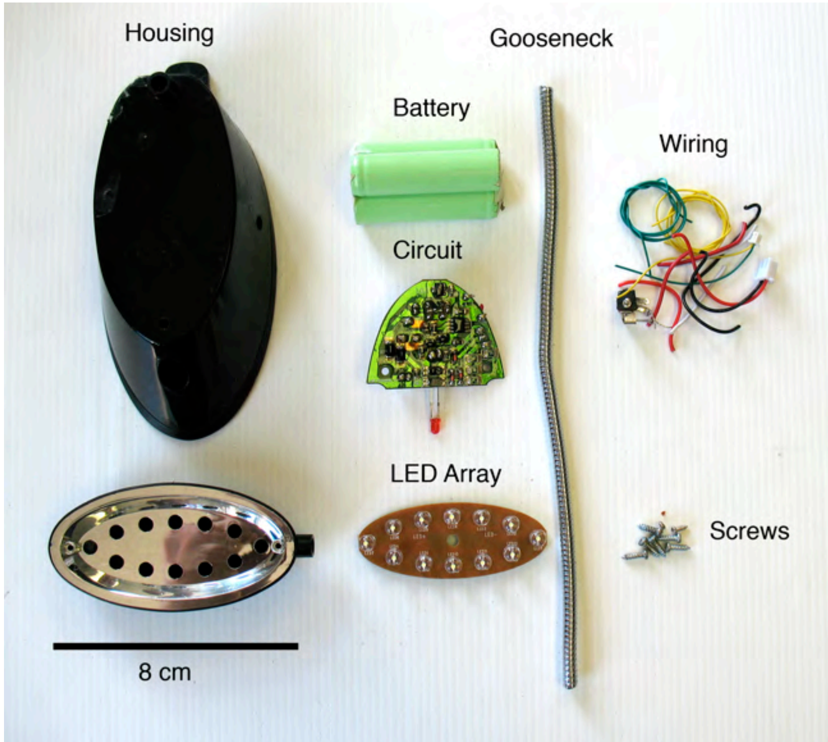


[B]

Figure 1: [A] The gooseneck lamp we offered for sale in Kenya with a 1 Watt CIS solar module. [B] A commercially available gooseneck lamp that was the basis for the lamp we sold. It has the same internal components. The pen and a 15 cm solid line are included for scale.



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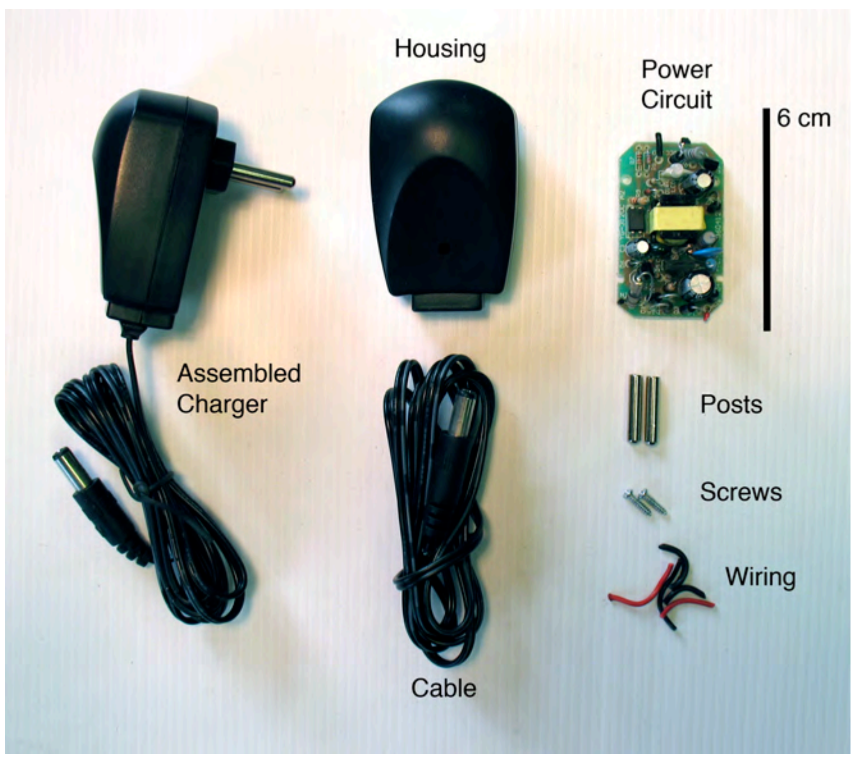

[B]

Figure 2: [A] Broken down LED lamp. [B] Broken down grid recharging circuit.

Our estimates for embodied energy in the commercially available LED task lights are summarized in Table 1, below. The details of the estimate, including each element of the embodied energy calculation, are provided in Appendix 2. Our estimates for total embodied energy are 62 MJ of primary energy for the grid-charged version (lamp + AC/DC adapter) and 143 MJ for the solar-charged version (lamp + PV module).

This analysis reflects estimates for a single product. For reference (as a loose proxy for embodied energy), the weight of this particular product is 148 grams. Weights of 5 other competing products range from 150 to 1200 grams (i.e., the task light we chose is among the lightest weight off-grid lighting products – and thus likely have lower embodied energy than is typical). The heaviest of the competing products, at 1200 grams, is a typical solar-fluorescent lantern—now being usurped by some LED systems. While we expect higher embodied energy for heavier lighting products in general, there may also be greater potential for primary energy (kerosene) offset by them if they provide better or longer-lasting lighting service to end-users.

Table 1: Embodied energy in LED task lights and charging accessories

Product	Component	Energy (MJ)
Lamp	NiMH Batteries	17
	5 mm LED Array	6
	Balance of System and Assembly	20
	Total	**43**
PV Module	PV Laminate Assembly	78
	Balance of System and Assembly	21
	Total	**100**
AC/DC Adapter	Power Electronics	15
	Balance of System and Assembly	4
	Total	**19**

Using a similar materials-processing method, we also estimated the embodied energy in hurricane kerosene lamps at 26 MJ (see Appendix 2 for details). While the energy requirements are slightly lower than those for either LED lighting product in the production phase, hurricane kerosene lamps consume nearly 2000 MJ of primary energy as kerosene fuel annually based on observations and measurements from our study.[2]

[2] We found users of hurricane lamps consumed ~150 mL of kerosene daily, based on observations and surveys.

Both solar and grid charged LED lamps have fast energy payback periods considering the amount of avoided kerosene we observed among adopters of LED lighting. The average user of LED lighting consumed 5.2 MJ of kerosene per night before adopting LED lighting and 2.8 MJ per night of kerosene after.[3] The users in our study uniformly chose to use grid recharging, with a median daily requirement of 0.5 MJ of primary energy to generate the required electricity based on the observed frequency of lamp recharging, the Kenya grid mix, and measured efficiency of the charging system.[4] Therefore, a total of 2.3 MJ primary energy use was avoided each day for the average user in the study. The result is an energy payback time of about one month for the grid-charged version of the LED lamp. None of the vendors chose to purchase a solar module for recharging, but, if they had, and kerosene use post-purchase remained unchanged relative to kerosene use for those who used the AC charged lamps, their payback time would have been approximately double, i.e., two months.

Figure 3 shows three embodied energy scenarios: the primary energy consumption over two years for (i) a grid charged LED lamp like the one we deployed, (ii) a corresponding solar charged LED lamp, and (iii) one month of kerosene offset by the LED lamps (considering that about 50% of the baseline kerosene was offset, which is cautious but also consistent with our field observations in the 2008 market test). The figure shows that over a two-year lifetime,[5] the solar charged option has higher primary energy requirements than the grid charged one.

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[3] The off-grid lighting users we studied were night market vendors in two Kenyan towns: Mai Mahiu and Karagita. Both towns are relatively small (<20,000) and located in the Rift Valley Province. Before our study, the vendors relied on various fuel-based lighting technologies to illuminate their nighttime businesses. We surveyed 50 vendors to establish baseline fuel use trends and carefully measured baseline lighting fuel use for a subset of 23 vendors. We then offered the opportunity to purchase an LED light with and without a solar charging option to the 23 for whom we had established a detailed baseline; 14 chose to purchase an improved lighting product. We tracked kerosene use, user satisfaction, and expenditures for lighting for all 23 vendors over a one-year period). The mean GHG emissions over the one-year study period for those who did not adopt LED lighting was 130 kg CO_2e/vendor-year from burning approximately 150 mL of kerosene a day. Those who purchased LED lights reduced their year-long emissions from burning kerosene by approximately 50% to 65 kg CO_2e/vendor-year; the mean kerosene consumption rate for them was 79 mL/day.

[4] The Kenya grid had a primary energy heat rate of 5.6 MJ/kWh in 2007 (KNBS, 2008), assuming that the thermal efficiency of hydroelectricity and geothermal electricity is unity and that the average efficiency of thermal, cogeneration, and imports is 33%. Based on the measured charging efficiency of the AC charger of 21% and assumed battery efficiency of 70%, the lamps we offered required 25 Wh of grid electricity for each charging cycle. The median observed recharging rate for the lamp users was once every three days.

[5] Our assumption is that the commercial version of the LED lamp we distributed has a lifetime of about two years, based on our extensive lab-based testing of off-grid lighting products (Mills and Jacobson 2007) and observations we made in the field of use patterns and the rigors of actual use. The modified lamps we distributed had shorter lifetimes in practice due to design flaws in the detachable lamp head and housing we used.

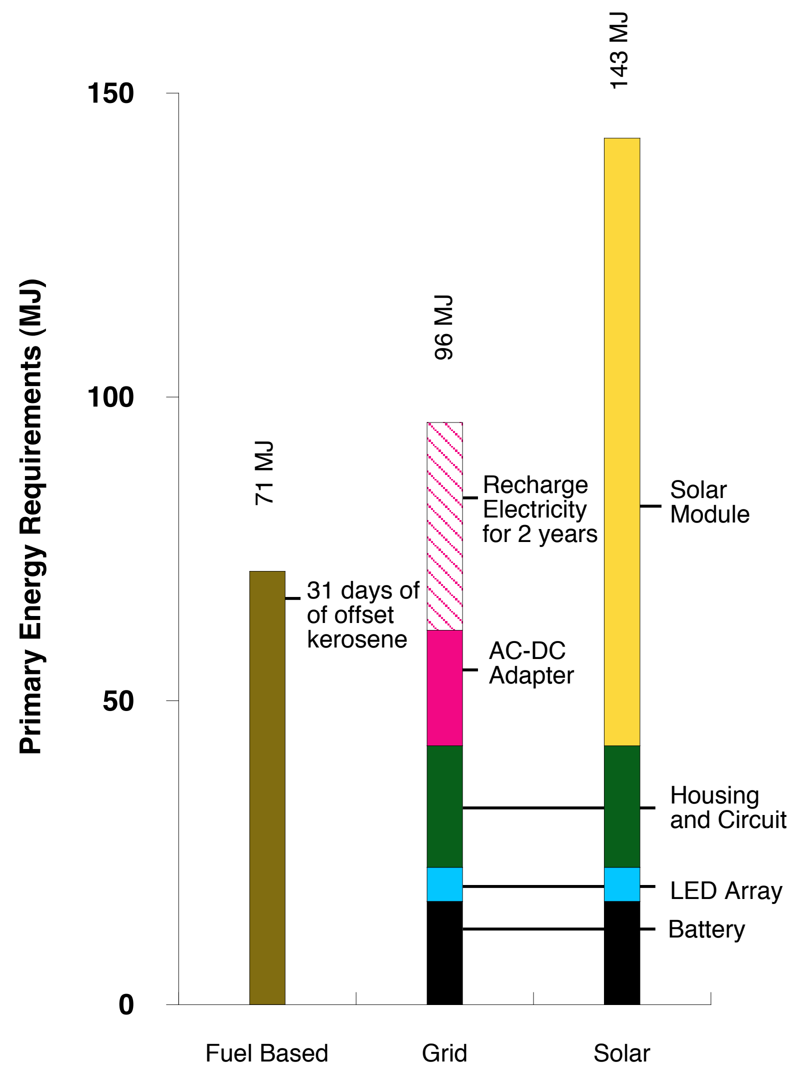

Figure 3: Primary energy embodied in LED lamps by component over a two-year period (two charging strategies) compared to one month of kerosene consumption for fuel-based lighting.

Energy Return on Investment

Off-grid LED lighting has a surprisingly fast energy payback period compared to other solar applications, which warrants a closer look. For instance, both grid and solar charged LED products appear to have substantially faster energy payback than kilowatt scale grid-connected solar PV systems, which have been the subject of several life cycle assessments and have payback periods ranging from 0.5-5.5 years depending on the technology and location (Fthenakis and Alsema, 2006; Alsema and de Wild-Scholten 2006; Raugei et al., 2007). However, a key point is that LED lighting product lifetimes are shorter than solar-electric systems in general.[6] Considering the energy return on investment (EROI) provides a fairer comparison between off-grid LED lighting and other energy technology interventions than energy payback period alone because it accounts for the difference in lifetime between the devices. We estimate EROI according to Equation 1 below.

Equation 1

$$EROI = E_{offset} / E_{embodied} \quad or \quad T_{lifetime} / T_{PBP}$$

where: EROI = energy return on investment (ratio)

E_{offset} = offset energy over the lifetime of the lamp (Joules)

$E_{embodied}$ = embodied energy to produce the lamp (Joules)

$T_{lifetime}$ = lifetime of product (years)

T_{PBP} = energy payback period of product (years)

Note that one can convert between EROI and energy payback period if the product lifetime is known by recognizing that the ratio between offset energy and embodied energy is the same as the ratio between the overall project (or product) lifetime and the energy payback period, as is shown in equations 2-4 in Appendix 3.

Based on our estimates, which are for a specific LED lamp in a particular context, about two months out of the two-year estimated product lifetime are devoted to paying energy debt for the solar charged version, resulting in an EROI of 12. The grid charged version pays twice as fast and has an EROI of 25. For grid-connected solar electric systems, 0.5-5.5 years out of a 25-year lifetime is devoted to energy debt – between 2 and 22% of the lifetime – resulting in an energy ROI of to 4.5 to 50. This places the 2008 LED task light EROI solidly among those of grid-

[6] Because LED lighting products are integrated systems, the failure of a single component, such as the battery, will lead to end-of-life unless it is easily replaceable. Also, like other consumer electronics, LED lighting is subject to greater mechanial stress (e.g. being dropped) than is typical for solar electric systems. Cost pressures can also lead to the production of inferior, short-lived products.

connected solar electric systems, and approximately equal to that of wind energy systems, which have an average energy ROI of about 20 based on a meta-analysis of operational wind generation projects by Kubeszewski et al., 2010. Compared to other lighting technology interventions, however, off-grid lighting is not as favorable in terms of EROI. For instance, estimates from a life cycle energy comparison of incandescent, CFL, and LED lights for the grid-connected market results in EROI values of over 250 in cases where incandescent are replaced by either CFLs or LEDs (Osram 2009).

Figure 4 shows the expected range in energy ROI depending on the percentage of fuel use that is offset and the product lifetime for a hypothetical solar LED lighting system that has 140 MJ of embodied primary energy and is being used by someone who previously used 5 MJ of fuel each night for lighting – a very similar situation to the one we observed. Our estimate for EROI is noted on the plot, corresponding to a value of 12 with a 2-year service lifetime at an offset fraction of 0.5. The plot shows that EROI is very sensitive to both durability and the percentage of lighting fuel that is offset. At the low end on the figure is an LED light that only lasts 6 months and offsets 10% of the baseline fuel use, resulting in a very low EROI of 0.65 (EROI of 1 is “break even,” so this worst-case situation represents a net increase in worldwide primary energy consumption). On the other hand, a lamp that offsets 100% of lighting fuel and lasts 5 years will have a greatly improved energy ROI of nearly 65.

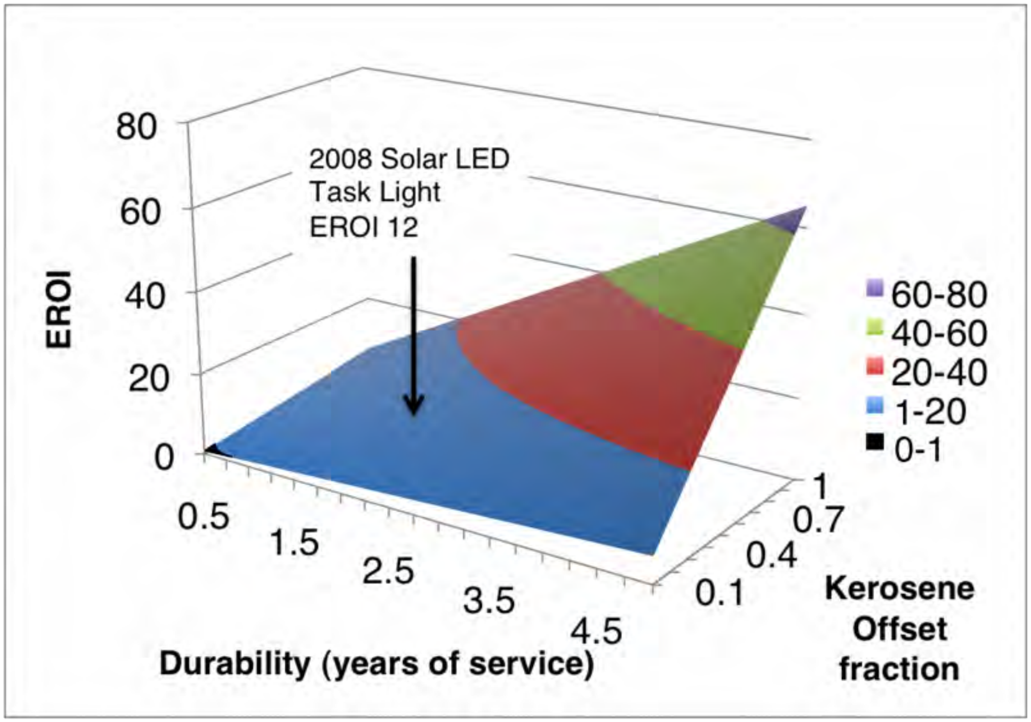

Figure 4: EROI for an LED lighting system with 140 MJ embodied energy that is used by someone with baseline fuel use of 5 MJ/day. Note that there is a black region that denotes EROI less than one – the region where the embodied energy is not "paid for" over the life of the product.

While the EROI of off grid solar home systems—a common technology intervention in rural areas of developing countries, often compares poorly with grid-connected solar electric systems (Alsema et al., 1998), LED lighting systems are already on par with grid connected solar and wind energy systems.[7] If anticipated improvements in LED lighting system performance (Lighting Africa, 2010) come to fruition, it seems likely that a greater fraction of the baseline emissions may be offset than we observed in this study because users will be less inclined to revert to or continue using fuel based lighting. Those gains, paired with improvements in durability, reparability, and the availability of replacement components could result in a hypothetical future LED lamp with energy ROI near the high end of those shown on Figure 4 or

[7] The main difference between SHS and LED lighting in this context is what one assumes is being offset; hypothetical alternative fuel-based electric generators are the baseline technology that is replaced in the case of Alsema et al.'s (1998) analysis, while very inefficient fuel-based lighting are often the baseline technology in the case of LED lighting systems. One could argue it is not appropriate to account for EROI for SHS in developing countries using Alsema et al.'s method because the alternative is not a generator but a continuation of the status quo; i.e., fuel based lighting and low levels of energy service. However, an extended analysis of EROI for SHS in developing countries is outside the scope of this work. In either case, the estimates of EROI and payback time from Alsema et al. for SHS provide a point of comparison for other technologies.

better, approaching 65. Such levels would exceed the best grid connected solar electric systems from 2005, but would not be on the same level as efficient lighting technology interventions for grid-connected consumers.

Conclusions

For a population of night market vendors we studied in 2008-2009, some of whom replaced fuel-based lighting with LED lighting, we estimate that the energy payback time for grid-charged LED lighting systems was approximately one month and would have been approximately two months for solar charged LED lighting systems if the vendors had chosen them.

In terms of EROI, LED lighting systems circa 2008 (EROI 12-24) compare favorably to grid-connected solar (EROI 5-50) and wind energy (EROI 20). Because the technology used in LED lighting systems is rapidly improving, we expect the EROI to improve in the future, approaching 65, which would place it above investments in renewable generation but not at the level of conventional efficiency measures in the grid-based lighting sector, which have EROIs of 250 or more.

Fast energy payback times for efficient off-grid lighting systems means that the greenhouse gas benefits begin to accrue nearly immediately once they are adopted; high EROIs indicate that the investment is also good compared to alternatives like solar or wind power. Our findings indicate that there should not be any preference for solar charged over grid charged lighting products in the context of greenhouse gas mitigation effectiveness when embodied energy is included in the analysis. However, for some users grid charging is infeasible due to a lack of access. Efficient off-grid lighting is effectively poised to make a near term dent in the estimated 190 million tonnes CO_2 that result from fuel based lighting (Mills 2005), and the embodied energy of production for this new class of consumer electronics is not a hindrance to that potential.

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Appendix 1: Publicly Available Embodied Energy Intensities

Table A1: Unit embodied energy factors for materials, components, and processes associated with off-grid lighting products. *We recommend the original source be reviewed before using the factors to estimate embodied energy.*

Category	Item	Value	Units	Boundary	Source	Note
Circuits	LED Driver Circuit ("Electronic Ballast")	1.125	MJ/W	Manufacturing Energy	Osram 2009	Based on 8 W driver for 6 high power LEDs
Circuits	Printed Circuit Board (PCB)	690	MJ/m2	Manufacturing Energy	Lee and Park 2001	Based on central estimate
Circuits	Printed Circuit Board 1/2 lay 3.75 kg/m2	281	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	Standard PCB (also known as printed wiring board, “PWB”)
Circuits	Printed Circuit Board 6 lay 4.5 kg/m2	367	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	Typical for computers, TVs, etc.
Circuits	Printed Circuit Board 6 lay 2 kg/m2	488	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	Typical for mobile computing products
Circuits	PV Charge Regulator	1	MJ/W	Materials and Manufacturing	Rydh and Sanden 2005	
Circuits	Inverter	1	MJ/W	Materials and Manufacturing	Rydh and Sanden 2005	
Components	EPROM Chip (M27C1001, 0.36 W IC)	12.5	MJ/chip	Production and Transport	Taiariol et al., 2001	
Components	Power Capacitors and Coils	383	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	
Components	"Large" Integrated Circuits (high estimate).	8022	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	

Category	Item	Value	Units	Boundary	Source	Note
Components	"Small" Integrated Circuits (low estimate).	1787	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	
Components	Surface mounted devices and LEDs (avg.)	2969	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	Includes diodes, thyristors, RF, resistors, etc.
Components	Lead-free solder	234	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	
Components	Slots and External Connectors for PCB	187	MJ/kg	Materials and Manufacturing	Kemma et al. 2005	
LED	LED Package	1.107	MJ/Wp	Front and Back End Processing	Osram 2009	Based on 0.41 kWh for 1x Golden Dragon Plus package (1.3 W)
LED	LED Package	3.6	MJ/LED	Manufacturing Process	Matthews et al 2009	Based on 1 kWh/chip estimate for high power LED
LED	200 mm wafer (general semiconductor)	17653	MJ/kg	Cradle to Gate	Duque Ciceri et al 2010	
Metal	Stainless Steel	56.7	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 50%
Metal	General Steel	35.3	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Refined Si	Semiconductor Grade Si	35000	MJ/kg	Unspecified	Taiariol et al. 2001	
Metal	Aluminum (extruded)	154	MJ/kg	Cradle to Gate	Hammond and Jones 2008	High Quality Data +/- 20%
Metal	Aluminum (metallurgical)	162	MJ/kg	Unspecified	Taiariol et al. 2001	
Metal	Copper (general)	69	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 50%
Metal	Copper (metallurgical)	20	MJ/kg	Unspecified	Taiariol et al. 2001	

Category	Item	Value	Units	Boundary	Source	Note
Plastic	General Plastic	80.5	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Plastic	ABS	95.3	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Plastic	Polycarbonate	112.9	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Plastic	High Impact Polystyrene	87.4	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Plastic	Polystyrene	87.2	MJ/kg	Unspecified	Thiriez and Gutowski 2006	
Plastic	HDPE	76.7	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Plastic	HDPE	75	MJ/kg	Unspecified	Taiariol et al. 2001	
Plastic	HDPE	89.8	MJ/kg	Unspecified	Thiriez and Gutowski 2006	
Plastic	PVC	59.2	MJ/kg	Unspecified	Thiriez and Gutowski 2006	
Plastic	PVC (Injection Molded)	95.1	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Plastic	Polypropelene	83	MJ/kg	Unspecified	Thiriez and Gutowski 2006	
Plastic	Polypropelene (Injection Molded)	115.1	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Glass	General Glass	15	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 30%
Fiber	Cotton	146	MJ/kg	Cradle to Gate	Hammond and Jones 2008	+/- 50+%

Category	Item	Value	Units	Boundary	Source	Note
Paper	Paperboard (e.g., packaging)	28	MJ/kg	Unspecified	Kemma et al. 2005	
Process	Injection Molding (Hydraulic)	18.97	MJ/kg	Raw plastic to finished case	Thiriez and Gutowski 2006	
Process	Injection Molding (Hybrid)	13.24	MJ/kg	Raw plastic to finished case	Thiriez and Gutowski 2006	
Process	Injection Molding (Electric)	12.57	MJ/kg	Raw plastic to finished case	Thiriez and Gutowski 2006	
Process	Circuit board-level assembly	130	MJ/kg	Manufacturing Energy	Duque Ciceri et al 2010	Central Estimate +/- 10 MJ/kg
Process	Circuit board-level assembly	128	MJ/kg	Unspecified	Kemma et al. 2005	
Process	Final Electronics Assembly	0.25	MJ/chip	Manufacturing Energy	Duque Ciceri et al 2010	Central Estimate +/- 0.05 MJ/kg
Process	Finish Machining (i.e., for metalworks)	24	MJ/kg	Manufacturing Energy	Duque Ciceri et al 2010	
Process	Milling (i.e., for metalworks)	1.95	MJ/kg	Manufacturing Energy	Duque Ciceri et al 2010	Central Estimate +/- 0.65 MJ/kg
Proces	Sheetmetal manufacturing	15	MJ/kg	Unspecified	Kemma et al. 2005	
Process	Final Assembly for Consumer Electronics	2962	MJ/m3	Manufacturing Floor to EU Retail	Kemma et al. 2005	Per m3 of packaged product; Includes assembly, warehouse, transport
Process	Final Assembly for General Appliances	700	MJ/m3	Manufacturing Floor to EU Retail	Kemma et al. 2006	Per m3 of packaged product; Includes assembly, warehouse, transport
Batteries	NiMH (virgin)	3.7	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	

Category	Item	Value	Units	Boundary	Source	Note
Batteries	NiMH (recycled)	2.7	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Batteries	Li-ion (virgin)	1.87	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Batteries	Li-ion (recycled)	1.51	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Batteries	Lead-Acid (virgin)	1.19	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Batteries	Lead-Acid (recycled)	0.87	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Batteries	NiCd (virgin)	4.1	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Batteries	NiCd (recycled)	3.1	MJ/Wh	Materials and Manufacture	Rydh and Sanden 2005	
Photovoltaics	CIS (laminated assembly, no frame)	27.7	MJ/W	Materials and Manufacture	Raugei et al. 2007	
Photovoltaics	CdTe (laminated assembly, no frame)	7.6	MJ/W	Materials and Manufacture	Raugei et al. 2008	
Photovoltaics	Ribbon Silicon (laminated assembly, no frame)	20.5	MJ/W	Materials and Manufacture	Alsema and de Wild-Scholten 2006	
Photovoltaics	Polycrystalline Silicon (laminated assembly, no frame)	22.3	MJ/W	Materials and Manufacture	Alsema and de Wild-Scholten 2006	
Photovoltaics	Monocrystalline Silicon (laminated assembly, no frame)	35.6	MJ/W	Materials and Manufacture	Alsema and de Wild-Scholten 2006	

Appendix 2: Details on Embodied Energy Estimate

Method

We accounted for each material, component, and process required to manufacture finished products for each of the embodied energy estimates we made. The method is similar to those outlined in Duque Ciceri et al., 2010 and Kemma et al., 2005. The following table details the estimates for four products: the commercially available (2008) LED lamp similar to the one we deployed during our study, the one-watt PV module that was available with the lamp, the wall charger that was included with a basic lamp purchase, and a hurricane kerosene lamp, the baseline technology for many people who use off-grid lighting. After the table, we have included explanatory notes on selected elements of the estimate.

Table A2 A-D: Embodied energy estimate details for (a) a commercially available (2008) LED task lamp, (b) a one Watt CIS PV module, (c) a four watt AC/DC wall charger, and (d) a hurricane kerosene lamp. For the wall charger and kerosene lamp, there are also estimates of the use-phase primary energy requirements for the devices on an annual basis.

A) LED Lamp	Component	Material Description	Qty.	Units	Energy (MJ)	Percent
1	Housing Material	ABS	49	g	4.7	11%
2	Housing Molding	Injection Molding	49	g	0.9	2%
3	Screws	Stainless steel	1.5	g	0.1	0%
4	Gooseneck	Stainless steel	18.1	g	1.0	2%
5	Wiring Conductor	Copper (assume 1/2 of wire mass)	1.55	g	0.1	0%
6	Wiring Insulation	General Plastic (assume 1/2 of wire mass)	1.55	g	0.1	0%
7	Control Circuit Board	PCB - 1 layer	3.24	g	0.9	2%
8	Control Circuit Connectors	Wire connectors	0.64	g	0.1	0%
9	Control Circuit SMD	Surface Mounted Devices	1.24	g	3.7	9%
10	LED Circuit Board	PCB - 1 layer	2.2	g	0.6	1%
11	12x 5mm through hole LEDs	Surface Mounted Devices	1.68	g	5.0	12%
12	Circuit Assembly	Board-level assembly for control and LED	9	g	1.2	3%
13	Battery	3x NiMH AA Package	4.7	Wh	17	41%
14	Packaging	Cardboard	62	g	1.7	4%
15	Final Assembly	Assembly, Shipping, Warehousing	1728	cm3	5.1	12%
	Total				**43**	**100%**

B) PV Module	Component	Material Description	Qty.	Units	Energy (MJ)	Percent
16	Laminate Assembly	CIS laminate assembly, 50% active area	1	W	78	79%
17	Frame	Extruded Aluminum	95	g	15	15%
18	Cable Conductor	Copper (assume 1/2 of cable mass)	25	g	1.7	2%
19	Cable Insulation	General Plastic (assume 1/2 of cable mass)	25	g	2.0	2%
20	Packaging	Cardboard	50	g	1.4	1%
21	Final Assembly	Assembly, Shipping, Warehousing	544	cm3	1.6	2%

	Total				**100**	**100%**

C) Wall Charger	**Component**	**Material Description**	**Qty.**	**Units**	**Energy (MJ)**	**Percent**
22	Housing Material	ABS	18.7	g	1.8	9%
23	Housing Molding	Hydraulic Injection Molding	18.7	g	0.4	2%
24	Circuit Board	PCB - 1 layer	4.26	g	1.2	6%
25	Power Conversion	Capacitors and Coils	8	g	3.1	16%
26	Control Electronics	Surface Mounted Devices	2.88	g	8.6	45%
27	Circuit Assembly	Board-level assembly for control and LED	15	g	2.0	10%
28	Cable Conductor	Copper (assume 1/2 of cable mass)	6.85	g	0.5	2%
29	Cable Insulation	General Plastic (assume 1/2 of cable mass)	6.85	g	0.5	2%
30	Wiring Conductor	Copper (assume 1/2 of wire mass)	0.2	g	0.01	0%
31	Wiring Insulation	General Plastic (assume 1/2 of wire mass)	0.2	g	0.01	0%
32	Posts and Screws	Stainless steel	4.5	g	0.3	1%
33	Packaging	Cardboard	9.2	g	0.3	1%
34	Final Assembly	Assembly, Shipping, Warehousing	192	cm3	0.6	3%
	Total (Production)				**19.0**	**100%**
35	**1 Year of Recharging**	Recharging cycle with Kenya grid mix	122	cycles	**17.1**	

D) Hurricane Lamp	**Component**	**Material Description**	**Qty.**	**Units**	**Energy (MJ)**	**Percent**
36	Metal Housing	Plain Steel	473	g	16.7	65%
37	Globe	General Glass	74	g	1.1	4%
38	Wick	Cotton	25	g	3.7	14%
39	Assembly	Assembly, Shipping, Warehousing	6030	cm3	4.2	16%
	Total (Production)				**25.7**	**100%**
40	**1 Year of Fuel Consumption**[8]	Kerosene	5.2	MJ/ day	**1898**	

[8] This estimate of fuel consumption rate is the baseline rate. We found that approximately 50% of the baseline was eliminated for users who adopted LED lighting.

PV Modules

During our analysis, we found that embodied energy data were not easily available for the small photovoltaic modules used in off-grid LED systems. There are a number of studies (Alsema et al., 2006, Raugei et al., 2006, etc.) that focus on "large" PV modules like the ones installed in grid-connected systems, but smaller modules can have higher embodied energy intensity because of their relatively lower fraction of active area and higher frame mass per watt. Figure A1 shows a range of PV modules that are typical of those offered with off-grid lighting products. The CIS module we focused on is labeled in the figure. Note that the fraction of active area is generally lower in these off-grid lighting modules than with typical grid-connected PV modules due to the use of semiconductor "seconds" (trimmings from large module wafers) and/or the setback area between the active area and the frame.

Figure A1: Various PV modules that are typical of those included with off-grid lighting products.

PV module primary energy requirements (PER) are composed of two primary components: the laminate assembly (which includes cells or active material, substrates, and covers) and the frame (Alsema and de Wild Schoelten 2006, Raugei et al. 2007, and others). In both parts, the PER for off-grid lighting products tends to be higher than typical. The frames of modules for off-grid lighting products tend to contribute more PER than for typical grid-connected modules due to their small relative size. Table A3 below also shows that while the majority (75-92%) of the PER for laminate assembly is for active cell material, the remainder goes towards the balance of materials and processing.

We propose the following method to account for the differences between typical modules and off-grid lighting modules in the context of embodied energy estimates:

1) Based on the module technology, find the primary energy requirements for a typical grid-connected laminated assembly (e.g., see Appendix 1.
2) Correct the primary energy requirement based on the active area fraction of the mobile module. Use values like those in Table A3 below with the following equation to "correct" the primary energy intensity for active area ratio.

Equation A1

$$PER_{oglp} = PER_{typ}\left(\left(\frac{1-CR_{oglp}}{1-CR_{typ}}\right)(1-\mu)+\mu\right)$$

where:

PER_{oglp}	=	Primary Energy Requirement for off-grid lighting product laminate assembly (MJ/W)
PER_{typ}	=	Primary energy requirement for typical laminate assembly (MJ/W)
CR_{oglp}	=	Cell to module area ratio ("active area ratio") for off-grid lighting product (fraction)
CR_{typ}	=	Cell to module area ratio ("active area ratio") for typical module (fraction)
μ	=	Fraction of PER_{typ} normally attributed to manufacture of active material (fraction)

3) Multiply the corrected primary energy requirement (PER_{oglp}) by the rated module power.
4) Add the appropriate energy for frame material (e.g., mass of extruded aluminum), cables, junction box, and final assembly.

For the CIS module we analyzed, the CR_{oglp} was 0.5. We assume that the fraction of primary energy in the laminate assembly that goes towards active area is the same for CdTe and CIS because we were unable to locate any works that showed the relative contribution of active material processing to laminate assembly PER for CIS. Therefore, the correction factor we calculated was [(0.5/0.06)*0.25 + 0.75] = 2.83 – meaning that the PER for the off-grid lighting product PV module we analyzed is about three times more energy intense per watt than typical grid connected CIS modules.

Table A3: Typical photovoltaic module LCA characteristic fractions

Technology	Cell to module area ratio [CR in eq. above]	Source	Fraction of laminate assembly energy for active material [μ in eq. above]	Source
Poly-Si (crystalline)	0.92	Alsema and de Wild Schoelten 2006	0.88	Alsema and de Wild Schoelten 2006
Mono-Si (crystalline)	0.92	Alsema and de Wild Schoelten 2006	0.92	Alsema and de Wild Schoelten 2006
Ribbon-Si (crystalline)	0.92	Alsema and de Wild Schoelten 2006	0.82	Alsema and de Wild Schoelten 2006
CIS	0.94	Alsema 1996	--*	--
CdTe	0.94	Alsema 1996	0.75	Kato et al. 2001

*Assume same as CdTe

LED Array

Embodied energy for LEDs is even more uncertain than many of the other components we considered. Matthews et al. (2009) give a preliminary estimate with large uncertainty of 1 kWh/LED package for high power LED packages. Osram (2009) also provides an estimate based on their manufacturing line: 0.41 kWh/LED for a “Golden Dragon Plus” 1.3 W package. Neither estimate includes the energy requirements of the materials that go into the process, the foremost of which is semiconductor grade silicon which has an estimated energy requirement of 35,000 MJ/kg (Taiariol et al. 2001). Also, both of the estimates are for “high power” surface mount LEDs, which are qualitatively different from the through-hole 5 mm LED's used in the product we analyzed.

To obtain an estimate of the energy required to manufacture the chip portion of the 5 mm LED, we used an estimate of the total embedded energy in a 200 mm semiconductor wafer from Duque Ciceri et al. (2010), 17653 MJ. We assume that the wafer yield is 50% (Bardsley et al. 2010) and that the diameter of the 5 mm chips is 0.35 mm (Krames 2003). This results in an estimate of 0.1 MJ per chip, which is vanishingly small in the context of this analysis. Based on the low chip energy requirements per LED, we assume that the unit energy factor for surface mounted devices, including LEDs, from Kemma et al. 2006 is applicable to 5 mm LEDs without any modification.

Appendix 3: Notes on energy pay back period and EROI

Equation 2 defines the energy payback period in terms of the embodied energy and the *rate* of energy offset (e.g., a product with 5 MJ embodied energy that offsets 2.5 MJ/year has a pay back period of 2 years).

Equation A2

$$T_{PBP} = \frac{E_{embodied}}{\dot{E}_{offset}}$$

Equation 3 defines the rate of energy offset in terms of the total offset energy and the lifetime (e.g., the rate of energy offset for a product that offsets a total of 25 MJ over a 10 year lifetime is 2.5 MJ/year).

Equation A3

$$\dot{E}_{offset} = \frac{E_{offset}}{T_{lifetime}}$$

Equation 4 combines equations 2 and 3 and rearranges to show that the ratio of lifetime to energy payback period is the same as the ratio of total offset energy to embodied energy (i.e., EROI).

Equation A4

$$\frac{T_{lifetime}}{T_{PBP}} = \frac{E_{offset}}{E_{embodied}}$$

Disclaimer