SUPPORTING INFORMATION FOR:

Alstone, P., P. Lai, E. Mills, and A. Jacobson. 2014. High life-cycle efficacy explains fast energy payback for improved off-grid lighting systems. *Journal of Industrial Ecology.*

Summary

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

Appendix S1: Publicly available embodied energy intensities

Table S1 (beginning next page)**:** Unit embodied energy factors for materials, components, and processes associated with off-grid lighting products and specific metrics for products involved in this study. The table includes estimates for the range of uncertainty of each metric based on the source as described in the main article. *We recommend the original source be reviewed before using the factors to estimate embodied energy.*

Reference	Code	Type	System	Component	Central Estimate	Lower Bound	Upper Bound	specified Uncertainty	General Uncertainty	Intensity	energyUnit	accntUnit	Boundary	Source	Type	Note
ref	*code*	*type*	*sys*	*comp*	*centEst*	*lower*	*upper*	*uncS*	*unc*	*int*	*energyU*	*accntU*	*bound*	*src*	*type*	*note*
1	qDriver	Energy	Circuits	LED Driver Circuit ("Electronic Ballast")	1.13	0.45	1.80		0.6	MJ/W	MJ	W	Manufacturing Energy	Osram 2009	ind	Based on 8 W LED driver
2	qPCB	Energy	Circuits	Printed Circuit Board (PCB)	690.00	414.00	966.00		0.4	MJ/m2	MJ	m2	Manufacturing Energy	Lee and Park 2001	peer	Based on central estimate
3	PCB-3.75	Energy	Circuits	Printed Circuit Board 1/2 lay 3.75 kg/m2	281.00	154.55	407.45		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	Standard PCB (or PWB)
4	PCB-4.5	Energy	Circuits	Printed Circuit Board 6 lay 4.5 kg/m2	367.00	201.85	532.15		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	Typical for computers, TVs, etc.
5	PCB-2	Energy	Circuits	Printed Circuit Board 6 lay 2 kg/m2	488.00	268.40	707.60		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	Typical for mobile computing products
6	pvReg	Energy	Circuits	PV Charge Regulator	1.00	0.60	1.40		0.4	MJ/W	MJ	W	Materials and Manufacturing	Rydh and Sanden 2005	peer	
7	inverter	Energy	Circuits	Inverter	1.00	0.60	1.40		0.4	MJ/W	MJ	W	Materials and Manufacturing	Rydh and Sanden 2005	peer	
8	eprom	Energy	Components	EPROM Chip (M27C1001, 0.36 W IC)	12.50	7.50	17.50		0.4	MJ/chip	MJ	chip	Production and Transport	Taiariol et al., 2001	peer	
9	qCapsCoils	Energy	Components	Power Capacitors and Coils	383.00	210.65	555.35		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	
10	qIC-large	Energy	Components	"Large" Integrated Circuits (high est).	8022.00	4412.10	11631.90		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	
11	qIC-small	Energy	Components	"Small" Integrated Circuits (low est.)	1787.00	982.85	2591.15		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	
12	qSMD	Energy	Components	Surface mounted devices and LEDs (avg.)	2969.00	1632.95	4305.05		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	Includes diodes, thyristors, RF, resistors, etc.
13	pbFreeSolder	Energy	Components	Lead-free solder	234.00	128.70	339.30		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	
14	qConnectors	Energy	Components	Slots and External Connectors for PCB	187.00	102.85	271.15		0.45	MJ/kg	MJ	kg	Materials and Manufacturing	Kemma et al. 2005	gov	
15	qLEDpack1	Energy	LED	LED Package	1.11	0.44	1.77		0.6	MJ/Wp	MJ	W	Front and Back End Processing	Osram 2009	ind	Based on 0.41 kWh for 1x Golden Dragon Plus package (1.3 W)
16	qLEDpack2	Energy	LED	LED Package	3.60	0.90	6.30		0.75	MJ/LED	MJ	package	Manufacturing Process	Matthews et al 2009	ppt	Based on 1 kWh/chip estimate for high power LED
17	LEDwafer	Energy	LED	200 mm wafer (general semiconductor)	17653.00	10591.80	24714.20		0.4	MJ/kg	MJ	kg	Cradle to Gate	Duque Cicera et al 2010	peer	
18	qSSteel	Energy	Metal	Stainless Steel	56.70	28.35	85.05	0.5	0.5	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 50%
19	qGSteel	Energy	Metal	General Steel	35.30	24.71	45.89	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
20	qSilicon	Energy	Metal	Semiconductor Grade Si	35000.00	14000.00	56000.00		0.6	MJ/kg	MJ	kg	Unspecified	Taiariol et al. 2001	conf	
21	qAl-ext	Energy	Metal	Aluminum (extruded)	154.00	123.20	184.80	0.2	0.2	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	High Quality Data +/- 20%
22	qAl-met	Energy	Metal	Aluminum (metallurgical)	162.00	64.80	259.20		0.6	MJ/kg	MJ	kg	Unspecified	Taiariol et al. 2001	conf	
23	qCu-gen	Energy	Metal	Copper (general)	69.00	34.50	103.50	0.5	0.5	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 50+%
24	qCu-met	Energy	Metal	Copper (metallurgical)	20.00	8.00	32.00		0.6	MJ/kg	MJ	kg	Unspecified	Taiariol et al. 2001	conf	
25	qPlastic	Energy	Plastic	General Plastic	80.50	56.35	104.65	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
26	qABS	Energy	Plastic	ABS	95.30	66.71	123.89	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
27	qPoly	Energy	Plastic	Polycarbonate	112.90	79.03	146.77	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
28	qHIPS	Energy	Plastic	High Impact Polystyrene	87.40	61.18	113.62	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
29	qPS	Energy	Plastic	Polystyrene	87.20	52.32	122.08		0.4	MJ/kg	MJ	kg	Unspecified	Thiriez and Gutowski 2006	peer	
30	qHDPE1	Energy	Plastic	HDPE	76.70	53.69	99.71	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
31	qHDPE2	Energy	Plastic	HDPE	75.00	30.00	120.00		0.6	MJ/kg	MJ	kg	Unspecified	Taiariol et al. 2001	conf	
32	qHDPE3	Energy	Plastic	HDPE	89.80	53.88	125.72		0.4	MJ/kg	MJ	kg	Unspecified	Thiriez and Gutowski 2006	peer	
33	qPVC	Energy	Plastic	PVC	59.20	35.52	82.88		0.4	MJ/kg	MJ	kg	Unspecified	Thiriez and Gutowski 2006	peer	
34	qPVC-moded	Energy	Plastic	PVC (Injection Molded)	95.10	66.57	123.63	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
35	qPP	Energy	Plastic	Polypropelene	83.00	49.80	116.20		0.4	MJ/kg	MJ	kg	Unspecified	Thiriez and Gutowski 2006	peer	
36	qPP-inject	Energy	Plastic	Polypropelene (Injection Molded)	115.10	80.57	149.63	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
37	qGlass	Energy	Glass	General Glass	15.00	10.50	19.50	0.3	0.3	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 30%
38	cotton	Energy	Fiber	Cotton	146.00	73.00	219.00	0.5	0.5	MJ/kg	MJ	kg	Cradle to Gate	Hammond and Jones 2008	db	+/- 50+%
39	paperboard	Energy	Paper	Paperboard (e.g., packaging)	28.00	15.40	40.60		0.45	MJ/kg	MJ	kg	Unspecified	Kemma et al. 2005	gov	
40	injectMold-hyd	Energy	Process	Injection Molding (Hydraulic)	18.97	11.38	26.56		0.4	MJ/kg	MJ	kg	Raw plastic to finished case	Thiriez and Gutowski 2006	peer	
41	injectMold-hybrid	Energy	Process	Injection Molding (Hybrid)	13.24	7.94	18.54		0.4	MJ/kg	MJ	kg	Raw plastic to finished case	Thiriez and Gutowski 2006	peer	
42	injectMold-elec	Energy	Process	Injection Molding (Electric)	12.57	7.54	17.60		0.4	MJ/kg	MJ	kg	Raw plastic to finished case	Thiriez and Gutowski 2006	peer	
43	circuitBoardAssem1	Energy	Process	Circuit board-level assembly	130.00	120.00	140.00	0.07692	0.07692	MJ/kg	MJ	kg	Manufacturing Energy	Duque Cicera et al 2010	peer	Central Estimate +/- 10 MJ/kg
44	circuitBoardAssem2	Energy	Process	Circuit board-level assembly	128.00	70.40	185.60		0.45	MJ/kg	MJ	kg	Unspecified	Kemma et al. 2005	gov	
45	finalAssem	Energy	Process	Final Electronics Assembly	0.25	0.20	0.30	0.2	0.2	MJ/chip	MJ	chip	Manufacturing Energy	Duque Cicera et al 2010	peer	Central Estimate +/- 0.05 MJ/kg
46	finishMachine	Energy	Process	Finish Machining (i.e., for metalworks)	24.00	14.40	33.60		0.4	MJ/kg	MJ	kg	Manufacturing Energy	Duque Cicera et al 2010	peer	
47	milling	Energy	Process	Milling (i.e., for metalworks)	1.95	1.30	2.60	0.3333	0.3333	MJ/kg	MJ	kg	Manufacturing Energy	Duque Cicera et al 2010	peer	Central Estimate +/- 0.65 MJ/kg
48	sheetmetalAssem	Energy	Proces	Sheetmetal manufacturing	15.00	8.25	21.75		0.45	MJ/kg	MJ	kg	Unspecified	Kemma et al. 2005	gov	
49	consElecAssem	Energy	Process	Final Assembly for Consumer Electronics	2962.00	1629.10	4294.90		0.45	MJ/m3	MJ	m3	Manufacturing Floor to EU Retail	Kemma et al. 2005	gov	Per m3 of packaged product; Includes assembly, warehouse, transport
50	generalAppAssem	Energy	Process	Final Assembly for General Appliances	700.00	385.00	1015.00		0.45	MJ/m3	MJ	m3	Manufacturing Floor to EU Retail	Kemma et al. 2006	gov	Per m3 of packaged product; Includes assembly, warehouse, transport
51	batt-nimh	Energy	Batteries	NiMH (virgin)	3.70	2.22	5.18		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	1.05
52	batt-nimh-recycled	Energy	Batteries	NiMH (recycled)	2.70	1.62	3.78		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
53	batt-liion	Energy	Batteries	Li-ion (virgin)	1.87	1.12	2.62		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
54	batt-liion-recycled	Energy	Batteries	Li-ion (recycled)	1.51	0.91	2.11		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
55	batt-pbacid	Energy	Batteries	Lead-Acid (virgin)	1.19	0.71	1.67		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
56	batt-pbacid-recycled	Energy	Batteries	Lead-Acid (recycled)	0.87	0.52	1.22		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
57	batt-nicd	Energy	Batteries	NiCd (virgin)	4.10	2.46	5.74		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
58	batt-nicd-recycled	Energy	Batteries	NiCd (recycled)	3.10	1.86	4.34		0.4	MJ/Wh	MJ	Wh	Materials and Manufacture	Rydh and Sanden 2005	peer	
59	pv-CIS	Energy	Photovoltaics	CIS (laminated assembly, no frame)	27.70	16.62	38.78		0.4	MJ/W	MJ	W	Materials and Manufacture	Raugai et al. 2007	peer	
60	pv-CDTE	Energy	Photovoltaics	CdTe (laminated assembly, no frame)	7.60	4.56	10.64		0.4	MJ/W	MJ	W	Materials and Manufacture	Raugai et al. 2008	peer	
61	pv-SiRibbon	Energy	Photovoltaics	Ribbon Silicon (laminated assembly, no frame)	20.50	12.30	28.70		0.4	MJ/W	MJ	W	Materials and Manufacture	Alsema and de Wild-Scholten 2006	peer	
62	pv-polySi	Energy	Photovoltaics	Polycrystalline Silicon (laminated assembly, no frame)	22.30	13.38	31.22		0.4	MJ/W	MJ	W	Materials and Manufacture	Alsema and de Wild-Scholten 2006	peer	
63	pv-monoSi	Energy	Photovoltaics	Monocrystalline Silicon (laminated assembly, no frame)	35.60	21.36	49.84		0.4	MJ/W	MJ	W	Materials and Manufacture	Alsema and de Wild-Scholten 2006	peer	
64	grid-kenya	Energy	electricity	Kenya Grid Mix	6.00	2.40	9.60	0.6	0.6	MJ/kWh	MJ	kWh	unspecified		author	
65	keroDailyKenyaObs2009	Energy	fuel	Daily kerosene offset - MMU users	5.10	-2.50	5.20	n/a	n/a	MJ	MJ	day	use in field - no upstream accounting			based on our observations in the field
66	rechargeDailyKenya	Rate	use	Daily recharging cycles	0.30	0.10	0.50	n/a	n/a	num	num	day	observed use in field			based on our observations in the field
67	customPvFactorBFP2008	Factor	factor	PV material multiplier -- BFP Firefly 2008	2.83	1.13	4.53	0.6	0.6	num	num	num	n/a	Author Estimates	author	
68	unityFreq	Factor	factor	Just a one -- use for "scaling" a daily use	1.00	1.00	1.00	0	n/a	num	num	num	n/a	Author Estimates	author	
69	pv-aSi	Energy	Photovoltaics	Amorphous Silicon, laminated assembly, no frame	1200.00	720.00	1680.00		0.4	MJ/m2	MJ	m2	unspecified	Alsema and Niewlaar 2000	peer	need to add this as a source
70	wick-emb	Energy	Finished Product	wick lamp embedded energy	1.00	0.25	1.75		0.75	MJ/lamp	MJ	num	unspecified	Donahoe and Boddy 2009	ppt	a student report, selected ppt due to higest uncertainty factor
71	kero-wick50	Energy	fuel	Daily kerosene offset - general wick lamp - 50% offset	1.44	-0.72	1.51	n/a	n/a	MJ/day	MJ	day	use in field - no upstream accounting	Baker and Alstone 2011	author	Assume same dist as observed in Kenya, scaled to mean comsumption in five-country study
72	kero-hurricane50	Energy	fuel	Daily kerosene offset - general hurricane lamp - 50% offset	6.14	-3.07	6.45	n/a	n/a	MJ/day	MJ	day	use in field - no upstream accounting	Baker and Alstone 2011	author	Assume same dist as observed in Kenya, scaled to mean comsumption in five-country study
73	kero-wick100	Energy	fuel	Daily kerosene offset - general wick lamp - 100% offset	1.44	1.15	1.73	n/a	n/a	MJ/day	MJ	day	use in field - no upstream accounting	Baker and Alstone 2011	author	Assume mean displacement equal to mean in five-country study, low/high variation = 20% of mean.
74	kero-hurricane100	Energy	fuel	Daily kerosene offset - general hurricane lamp - 100% offset	6.14	4.91	7.37	n/a	n/a	MJ/day	MJ	day	use in field - no upstream accounting	Baker and Alstone 2011	author	Assume mean displacement equal to mean in five-country study, low/high variation = 20% of mean.
75	customPvFactorA	Factor	factor	PV material multiplier --Product A	1.00	0.40	1.60	0.6	0.6	num	num	num	n/a	Author Estimates	author	
75	customPvFactorB	Factor	factor	PV material multiplier --Product B	1.18	0.47	1.89	0.6	0.6	num	num	num	n/a	Author Estimates	author	
75	customPvFactorC	Factor	factor	PV material multiplier --Product C	1.53	0.61	2.45	0.6	0.6	num	num	num	n/a	Author Estimates	author	
75	customPvFactorD	Factor	factor	PV material multiplier --Product D	1.34	0.54	2.14	0.6	0.6	num	num	num	n/a	Author Estimates	author	
75	customPvFactorE	Factor	factor	PV material multiplier --Product E	1.00	0.40	1.60	0.6	0.6	num	num	num	n/a	Author Estimates	author	
75	customPvFactorF	Factor	factor	PV material multiplier --Product F	1.18	0.47	1.89	0.6	0.6	num	num	num	n/a	Author Estimates	author	
75	customPvFactorG	Factor	factor	PV material multiplier --Product G	1.16	0.46	1.86	0.6	0.6	num	num	num	n/a	Author Estimates	author	

Appendix S2: Details on embodied energy estimates

Summary of Calculations

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 steps represent a general algorithm for our analysis and could be applied to other OGL products, or, more broadly with some modifications, to other rural development technology that is adopted based on benefits that correlate with overall reductions in primary energy use:

1. Observe and measure the impact of technology adoption on actual end-users. Use "before and after" measurements of energy consumption to estimate the quantity (and uncertainty in the estimate) for energy and other impacts from technology adoption. Use study data, expert opinion and user feedback to estimate the expected lifetime energy offsets. This is a key step and can help understand and manage a major source for uncertainty in the estimates.
2. Tear down the physical product into constituent parts and measure each unit (mass or quantity). Account for both physical materials, materials processing, and transportation-related steps.
3. Identify reputable, trusted sources for the central estimate of unit energy intensity for each constituent part. For off-grid lighting and other similar electronics, a starting point could be the data we include in the supporting information.
4. Estimate the uncertainty in unit energy intensity by identifying a reasonable upper and lower bound to establish triangular distributions around each central estimate.
5. Find the central estimate for embodied energy by summing the product of the central estimates for each unit of energy intensity and the measured quantities of each material and process.
6. Estimate energy payback period, energy return on investment, life cycle efficacy, and/or other performance metrics that apply to the context using the central estimates for embodied energy and energy offset.
7. Establish bounds on the estimates using Monte Carlo techniques.

The following table details the central 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. Similar estimates were made for a range of products available in 2012, but the details are not presented here to protect the confidentiality of the products. The range of estimates, accounting for uncertainty, is not presented here but is shown in the main document.

Single vs. Grouped Uncertainty

We propose two types of Monte Carlo run for use in this study: one to estimate the uncertainty for a single end-user and another to estimate the uncertainty in average impact for a group of 1,000 end users. In the case of a single end user, "all" of the uncertainty is present (both upstream embodied energy and downstream kerosene offsets and grid electricity use). In the case of groups of users, the upstream energy is essentially the same per-user since OGL are mass-produced but the fuel consumption patterns for each of the 1,000 users is variable. We take the mean consumption pattern for the group to estimate the net energy impacts for the group. The group results are more useful than single-user results for considering the aggregate impacts of broad market adoption; they are the focus in our results.

Table S2 A-D: Embodied energy central 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	**32.0**	

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**[a]	Kerosene	5.2	MJ/ day	**1898**	

[a] 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. More details are available in Supporting Information Part 4.

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 that focus on "large" PV modules like the ones installed in grid-connected systems (Alsema, K. Kato, and P. Frankl 1998; Raugei, Bargigli, and Ulgiati 2007), 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 S1: 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-Scholten 2006; Raugei, Bargigli, and Ulgiati 2007) 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 Table A1).
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 S1

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

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 estimate is [(0.5/0.06)*0.25 + 0.75] = 2.83 – meaning that the PER for the off-grid lighting product PV module we analyzed may be three times more energy intense per watt than typical grid connected CIS modules. Since the true value of this factor is not established and the approach we take is speculative, we assign a +/- 60% uncertainty to the value in the error analysis, and assume a triangular distribution of likely values centered at our estimate .

Table S3: 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-Scholten 2006)	0.88	(Alsema and de Wild-Scholten 2006)
Mono-Si (crystalline)	0.92	(Alsema and de Wild-Scholten 2006)	0.92	(Alsema and de Wild-Scholten 2006)
Ribbon-Si (crystalline)	0.92	(Alsema and de Wild-Scholten 2006)	0.82	(Alsema and de Wild-Scholten 2006)
CIS	0.94	(Alsema, K. Kato, and P. Frankl 1998)	--*	--
CdTe	0.94	(Alsema, K. Kato, and P. Frankl 1998)	0.75	Kato et al. (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 marginally different from the through-hole 5 mm LED's used in some of the products we analyzed.

As a point of comparison we make an estimate of the energy required to manufacture the chip portion of 5 mm LEDs. It is based on an estimate of the total embedded energy in a 200 mm semiconductor wafer from Duque Ciceri et al. 17,653 MJ (Duque Ciceri, Gutowski, and Garetti 2010),. We assume that the wafer yield is 50% (Bardsley Consulting 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 a unit energy factor of 3 MJ/gram for surface mounted devices, including LEDs, from Kemma et al.*(2005)* is applicable to the 5 mm LEDs and other SMD LEDs in OGL products. This gives results that are roughly in line with estimates for SMD LEDs from the sources mentioned above (Matthews et al. 2009; Osram 2009) given the mass of LED chips.

Upstream Emissions from Primary Energy Production

Marginal increases or decreases in primary energy consumption have upstream impacts in the fossil fuel supply chain, where additional fossil fuel is required during each phase from extraction to delivery. The best practice is to account for these using an upstream emissions factor.

We assume that the authors of the studies and reports we base our materials processing estimates on have included upstream emissions factors. There is mixed evidence in their articles and reports, with some mentioning it and many not specifying whether it is accounted for explicitly. To avoid double counting, we do not apply any additional upstream energy factor to those estimates.

We also make our own estimates of primary energy consumption for kerosene in a range of countries in Sub-Saharan Africa. To account for upstream energy consumption in those estimates we first use information on upstream greenhouse gas emissions factors for kerosene and the overall emissions factor to estimate the fraction of the overall factor that is upstream. We then apply this to a lower heating value estimate for the energy intensity of kerosene, assuming that greenhouse gas emissions roughly correlate with primary energy consumption in the case of kerosene that is in general use (not necessarily for this specific use case, which we described as having particularly high black carbon emissions during use).

It may be the case that in this particular market, which is characterized by diffuse and informal sellers at the retail end of the supply chain (Tracy and Jacobson 2012), the fraction of fuel that is lost to actual leakage and spills is larger than in typical fuel supply chains. In spite of this hypothesis, we do not revise the upstream energy requirements.

Table S4: Upstream vs. downstream greenhouse gas emissions for kerosene in household applications.

Emissions Type	**Factor (gCO_2e/MJ)**	**Source**
Exploration	6.9	(UNFCCC 2013)
Transport of Crude Oil	1.5	(UNFCCC 2013)
Upgrade	1.9	(UNFCCC 2013)
Transport of Refined Product	0.9	(UNFCCC 2013)
Total Upstream	**11.2**	(UNFCCC 2013)
Total Downstream	**72.15**	(IPCC 2006)
Upstream Fraction	*16%*	*calculation*

The lower heating value of kerosene is 34.45 MJ/liter (IEA 2008), and we apply the 16% upstream factor from emissions to it for a full estimate of 41 MJ/liter that accounts for upstream leakage. This energy intensity factor is used throughout the analysis.

Kenya Grid Primary Energy

The Kenya grid includes both hydroelectric and oil-burning thermal plants that can operate on the margin (Kenya National Bureau of Statistics 2008). We assume the additional load from grid

charging lamps is equally likely to come from either hydroelectricity or thermal plants that have an efficiency of 33%; both sources are assigned 10% line losses. This results in an estimate for the average marginal primary energy intensity of 6 MJ/kWh. 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 (Alstone et al. 2013). This results in a daily primary energy use of 0.05 MJ.

Appendix S3: Notes on the relationship between energy payback period and EROI

Equation S2 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 S2

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

Equation S3 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 S3

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

Equation S4 combines equations S2 and S3 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 S4

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

Appendix S4: Details on the broad market analysis

We estimate the "typical" impacts for adopting improved off-grid lighting products with a combination of data from different sources. The average consumption of kerosene for each appliance is from a Lighting Africa market research synthesis report (Baker and Alstone 2011) and they are summarized in Table S5 below.

We assume that the cost of fuel in each of these markets is US$1/liter (Tracy and Jacobson 2012) and use a population-weighted average to find the typical consumption for hurricane and wick lamps and the fuel value of kerosene to estimate the typical energy use for hurricane lamps (6.96 MJ/day) and wick lamps (1.64 MJ/day).

Table S5: Estimates for kerosene consumption across five countries (Baker and Alstone 2011).

	Monthy expenditure for fuel (US$ / month 2008)			
Country	**Hurricane Lamp**	**Wick Lamp**	**Batteries for Flashlight**	**Candle**
Ethiopia	3.3	0.90	0.90	0.30
Ghana	3.5	4.7	2.3	4.7
Kenya	3.2	2.4	2.3	1.4
Tanzania	8.1	2.8	1.4	0.8
Zambia	5.1	2.4	2.3	1.5
Population-weighted Average	5.1	1.2	1.2	1.4

Appendix S5: Comparison with EIO-LCA

We use Economic Input-Output LCA (EIO-LCA) a point of comparison and cross-check for our process-based LCA results. Figure S2 below shows results from our model compared to EIO-LCA estimates for Electronic Appliances manufactured in China (using a 2002 dataset). We used online EIO-LCA software (www.eiolca.net) to make the estimates (Carnegie Mellon University Green Design Institute 2013) and an exchange rate of US$0.16 / 1 yuan that was estimated on August 13, 2013 using tools built into google.com search. This results in a basic estimate of 19.39 MJ per US$ in product value. We use estimated wholesale (FOB) prices for the products in this study as a benchmark value for the embodied energy. This economic boundary means these EIO-LCA estimates are not strictly equivalent in scope as the process-based estimates we made that included distribution energy; they are however a reasonably good comparison because the distribution only accounted for <5% of the process-based estimate.

The EIO-LCA estimates are relatively well correlated with our process-based estimates and are on the same order of magnitude. The average deviation between the two sets of estimates results in approximately 3x higher estimates from the EIO-LCA tool than the process-based approach we used. It is notable that while there is a linear deviation factor, the linear relationship that is intrinsic in EIO-LCA approaches seems to hold across the range of products we assessed. A "quick" estimate for embodied energy is therefore possible for an arbitrary product of a given wholesale price if one uses the correction factor we estimate here (a factor of 2.6), and would result in a reasonably good estimate depending on the context.

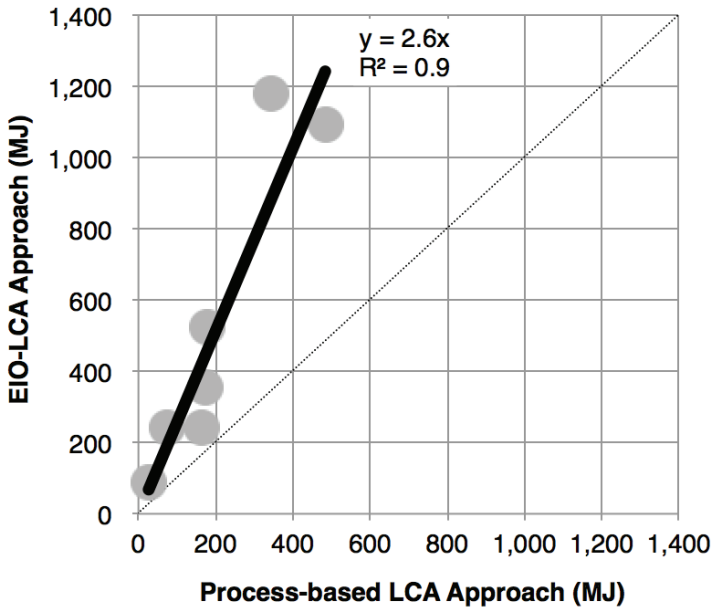

Figure S2: Comparison between EIO-LCA and process-based approaches for estimates of embodied energy in off-grid lighting products. EIO-LCA data are from an online tool (Carnegie Mellon University Green Design Institute 2013). The dotted, diagonal line is a one-to-one relationship for reference.

Appendix S6: Fuel Based Lighting Technology

There are four key fuel-based lighting technologies that are of interest for this and similar analyses. They are pictured in the figure below and described in the table.

Pressure Lamp (13/50) | Hurricane Lamp (31/50) | Tin Lamp (1/50) | Candle (2/50)

Figure S3: The range of fuel-based lights used by participants in the field study with the number of night market vendors out of 50 participants who used each as their baseline primary lamp. (Adapted from Alstone et al. *(2013)*)

Table S6: Comparison of fuel-based lighting options.

Name	**Approximate Luminous Flux (lm)**	**Notes**
Pressure Lamp	350-500	Pressurized fuel, high burn rate. Most efficient fuel-based lamp.
Hurricane Lamp	20	Wick height determines burn rate. Wick is protected from wind.
Tin Lamp	10	Wick height determines burn rate. Wick is exposed to wind. Often made by artisans from repurposed cans and canisters.
Candle	10	A lamp made of fuel.

Appendix S7: Next Steps

The method we implemented for this work combined field and laboratory techniques to understand how the dynamics of technology adoption in markets influences life cycle energy benefits. We recommend several next steps to advance and apply the techniques:

- Continue to improve life-cycle performance estimates for OGL. Of particular importance are baseline and post-adoption kerosene offset fractions for a larger variety of OGL product options and contexts and a better understanding of the energy offsets and impacts from gaining access to non-lighting energy services that many OGL provide. Work to systematize analysis like the one presented here for global tracking of clean energy development, including implementing studies with similar frameworks on other rural energy technologies. A natural next step is implementing a study like this one for improved cookstoves.
- Continue work to support the growing but nascent market for OGL with good information to support and validate quality and performance factors that lead to good life-cycle performance.
- Link with detailed estimates for other key indicators of performance in the life cycle analysis that go beyond the primary energy impacts, such as greenhouse gas emissions, economic impacts on the end-user, and public health outcomes. Accounting for the spatial importance of impacts (i.e., important for public health, not as much for many greenhouse gases) could lead to interesting results.

References

Alsema, Erik. 1996. "Environmental Aspects of Solar Cell Modules: Summary Report". 96074. Utrecht University.

Alsema, Erik, and Mariska de Wild-Scholten. 2006. "Environmental Impacts of Crystalline Silicon Photovoltaic Module Production." In *13th CIRP International Conference on Life Cycle Engineering*. Leuven.

Alsema, Erik, K. Kato, and P. Frankl. 1998. "Energy Pay-Back Time of Photovoltaic Energy Systems: Present Status and Prospects." In *2nd World Conference on Photovoltaic Energy Conversion*. Vienna.

Alstone, Peter, Kristen Radecsky, Arne Jacobson, and Evan Mills. 2013. "The Dynamics of Off-Grid Lighting Adoption". Technical Report #12. Lumina Project. http://light.lbl.gov/pubs/tr/Lumina-tr12-lighting-adoption.pdf.

Baker, Melissa, and Peter Alstone. 2011. "The Off-Grid Lighting Market in Sub-Saharan Africa: Market Research Synthesis Report." Lighting Africa. IFC and the World Bank. http://www.lightingafrica.org/component/docman/doc_download/128-market-research-synthesis-.

Bardsley Consulting, Navigant Consulting, Radcliffe Advisors, SB Consulting, and Solid State Lighting Services. 2010. "Solid State Lighting Research and Development: Manufacturing Roadmap". Lighting Research and Development, Building Technologies Program, Office of Energy Efficiency, USDOE. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2010.pdf.

Carnegie Mellon University Green Design Institute. 2013. "Economic Input-Output Life Cycle Assessment (EIO-LCA) China 2002 (122) Model [Internet]." www.eiolca.net.

Donohoe, S, and M Boddy. 2009. "LED/Solar/NiMH vs. Kerosene vs. Candles". Final Report. UC Davis. http://piet1.ucdavis.edu/projects/zambia-bangladesh/ReplacingFuelBasedLighting2009DLabIFinalReport.pdf/view.

Duque Ciceri, N, T Gutowski, and M Garetti. 2010. "A Tool to Estimate Materials and Manufacturing Energy for a Product." In *IEEE/International Symposium on Sustainable Systems and Technology*. Washington, D.C.

Hammond, G, and C Jones. 2011. "Inventory of Carbon and Energy Version 1.6a". University of Bath. http://www.bath.ac.uk/mech-eng/sert/embodied.

IEA. 2008. "CO2 Emissions from Fuel Combustion". International Energy Agency. http://wds.iea.org/wds/pdf/doc_co2_2008.pdf.

IPCC. 2006. "2006 IPCC Guidelines for National Greenhouse Gas Inventories". IPCC. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Kato, K, T Hibino, K Komoto, S Ihara, S Yamamoto, and H Fujihara. 2001. "A Life-Cycle Analysis on Thin-Film CdS/CdTe PV Modules." *Solar Energy Materials & Solar Cells* 67: 279–287.

Kemma, R, M van Elburg, W Li, R van Holsteijn, and D Park. 2005. "Methodology Study of Eco-Design of Energy-Using Products ('MEEuP') Final Report". European Commission.

Kenya National Bureau of Statistics. 2008. "Statistical Abstract 2008". Nairobi: Kenya National Bureau of Statistics.

Krames, M. 2003. "Progress and Future Direction of LED Technology." In *SSL Workshop Proceedings*. Arlington, VA. apps1.eere.energy.gov/buildings/publications/pdfs/ssl/krames.pdf.

Matthews, H, D Matthews, P Jaramillo, C Weber, and C Hendrickson. 2009. "Life Cycle Assessment of Solid State Lighting Applications." http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/matthews_ssl09.pdf.

Osram. 2009. "Executive Summary: Life Cycle Assessment of Illuminants: A Comparison of Light Bulbs, Compact Fluorescent Lamps, and LED Lamps". Osram Opto Semiconductors GmbH. http://www.osram-os.com/osram_os/EN/About_Us/We_shape_the_future_of_light/Our_obligation/LED_life-cycle_assessment/OSRAM_LED_LCA_Summary_November_2009.pdf.

Park, Pilju, and Kun Mo Lee. 2001. "Application of Life-Cycle Assessment to Type III Environmental Declarations." *Environmental Management* 28 (4) (May): 533–546. doi:10.1007/s002670010242.

Raugei, Marco, Silvia Bargigli, and Sergio Ulgiati. 2007. "Life Cycle Assessment and Energy Pay-Back Time of Advanced Photovoltaic Modules: CdTe and CIS Compared to Poly-Si." *Energy* 32 (8) (August): 1310–1318. doi:10.1016/j.energy.2006.10.003.

Rydh, C, and B Sanden. 2005. "Energy Analysis of Batteries in Photovoltaic Systems. Part I: Performance and Energy Requirements." *Energy Conversion and Management* 46 (11-12) (July): 1957–1979. doi:10.1016/j.enconman.2004.10.003.

Taiariol, F, P Fea, C Papuzza, R Casalino, E Galbiati, and S Zappa. 2001. "Life Cycle Assessment of an Integrated Circuit Product." In *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment*, 128–133.

Thiriez, A, and T Gutowski. 2006. "An Environmental Analaysis of Injection Molding." In *Proceedings of the 2006 IEEE Int'l Symposium on Electronics and the Environment*, 195–200. http://web.mit.edu/2.810/www/Thiriez_ISEE_2006.pdf.

Tracy, Jennifer, and Arne Jacobson. 2012. "The True Cost of Kerosene in Rural Africa". Lighting Africa. http://www.lightingafrica.org/component/docman/doc_download/237-kerosene-pricing-lighting-africa-report.html.

UNFCCC. 2013. "Upstream Leakage Emissions Associated with Fossil Fuel Use". version 01.0.0. UNFCCC. http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-15-v1.pdf.