ENVIRONMENT

The Specter of Fuel-Based Lighting

Evan Mills

Thomas Edison's seemingly forward-looking statement that "we will make electricity so cheap that only the rich will burn candles" (*1*) was true for the industrialized world, but it did not anticipate the plight of 1.6 billion people (*2*)—more than the world's population in Edison's time—who more than a century later still lack access to electricity (see figure, this page). While electricity was becoming available in the wealthier countries, leaders of the oil industry (*3*, *4*) promoted lighting-oil products in China and elsewhere. The legacy of costly and low-grade lighting for the world's poor remains. For those without access to electricity, lighting is derived from a diversity of sources, including kerosene, diesel, propane, biomass, candles, and yak butter. Many of the 35 million people living in camps for refugees and internally displaced people have no light at all.

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Throughout the developing world, 14% of urban households and 49% of rural households were without electricity as of the year 2000 (*2*). In extreme cases, e.g., Ethiopia and Uganda, only ~1% of rural households are electrified (*5*). An unknown additional number of people have intermittent access to electricity in their homes or lack it altogether in their workplaces, markets, schools, or clinics (*6*). The number and proportion of people lacking electricity is growing in sub-Saharan Africa and parts of Latin America and the Caribbean, the Middle East, and South Asia (*7*). Population growth, stalling rates of electrification, and declining household sizes (*8*) exacerbate the problem. The number of people without access to electricity globally is projected to decline at only 0.4%/year over the next 3 decades (*2*).

Illumination is one of the core end-use energy services sought by society and is today obtained by some at efficiencies on the order of 100 lumens per watt and by others at well below 1 lumen per watt (*9*). Compounding this disparity, the least efficient sources also deliver less—and less uniform—light: A simple wick lantern provides about 1 lux (lumens/m^2) at 1 meter from the source, compared with levels on the order of 500 lux routinely provided in industrialized countries (figs. S1 to S3).

Although the energy performance of individual fuel-based light sources has been analyzed previously (*9*, *10*), the global dimensions have not been quantified. We estimate that fuel-based lighting is responsible for annual energy consumption of 77 billion liters of fuel worldwide (or 2800 petajoules, PJ), at a cost of \$38 billion/year or \$77 per household (table S1). This equates to 1.3 million barrels of oil per day, on a par with the total production of Indonesia, Libya, or Quatar, or half that of prewar Iraq. Consumption of lighting fuel is equivalent to 33% of the total primary energy (electricity plus fuel) used for household lighting globally and 12% of that across all lighting sectors (*11*).

Tailor working by candlelight in an "electrified" village in India.

Used 4 hours a day, a single kerosene lantern emits over 100 kg of the greenhouse gas carbon dioxide into the atmosphere each year. The combustion of fuel for lighting consequently results in 190 million metric tonnes per year of carbon dioxide emissions, equivalent to one-third the total emissions from the U. K.

Although about one in four people obtain light exclusively from fuel, representing about 17% of global lighting energy costs, they receive only 0.1% of the resulting lighting energy services (lumen hours). Despite the paucity of lighting services obtained, individual unelectrified households in the developing world spend a comparable amount of money on illumination as do households in the industrialized world.

Fuel-based lighting embodies enormous economic and human inequities. The cost per useful lighting energy services (\$/lux-hour of light, including capital and operating costs) for fuel-based lighting is up to ~150 times that for premium-efficiency fluorescent lighting (see figure, next page). The total annual light output (about 12,000 lumen-hours) from a simple wick lamp is equivalent to that produced by a 100-watt incandescent bulb in a mere 10 hours.

By virtue of its inefficiency and poor quality, fuel-based light is hard to work or read by, poses fire and burn hazards, and compromises indoor air quality. Women and children typically have the burden of obtaining fuel (*12*, *13*). Availability of lighting is linked to improved security, literacy, and income-producing activities in the home (*14*). Fuel prices can be highly volatile (*15*), and fuels are often rationed, which leads to political and social unrest, hoarding, and scarcity.

Although sometimes driven by good intentions such as reducing demand for fuel wood, fuel subsidies divert public sector funds from other uses. In India, where nearly 600 million people are without electricity, kerosene and liquid propane gas subsidies are of the same magnitude as those for education (*16*). Subsidies also create price distortions that discourage conservation and encourage dangerous and polluting fuel adulteration in the domestic and transport sectors (*17*, *18*).

Centralized rural electrification has its own problems, not the least of which is the cost of distribution in rural areas with low load densities, coupled with the high capital costs and low efficiencies associated with thermal power generation. Power theft levels reach 40% in some countries (*2*).

Off-Grid Solid-State Lighting: An Opportunity for Technological Leapfrogging

As they modernize, developing countries can select better technologies and in so doing surpass levels of efficiency typical of industrialized countries (*19*). The latest improvement in lighting energy efficiency is the solid-state white light–emitting diode (WLED) (*20*), distinguished from other lighting technologies by a continuing trend toward increasing light output, declining costs per unit of output, and rising efficiencies.

WLED technologies provide more and better illumination (with easier optical control) than do fuels (fig. S4), dramatically reducing operating costs (table S2) and greenhouse gas emissions, while increasing the quality and quantity of lighting services. Efficiencies of only five delivered lumens per watt in the mid-1990s are moving toward 100 lumens per watt (compared with 0.1 lumens per watt for a flame-based lantern). Relative

CREDIT: EVAN MILLS

The author is at the U.S. Department of Energy's Lawrence Berkeley National Laboratory, MS 90-4000, Berkeley, CA 94720, USA. E-mail: emills@lbl.gov

light output (assuming 1-watt WLEDs) would be 5 lumens, 100 lumens, and 40 lumens, respectively. Coupled with inexpensive diffusers or optics, today's best WLEDs deliver 10 to 100 times as much light to a task as do traditional fuel-based lanterns.

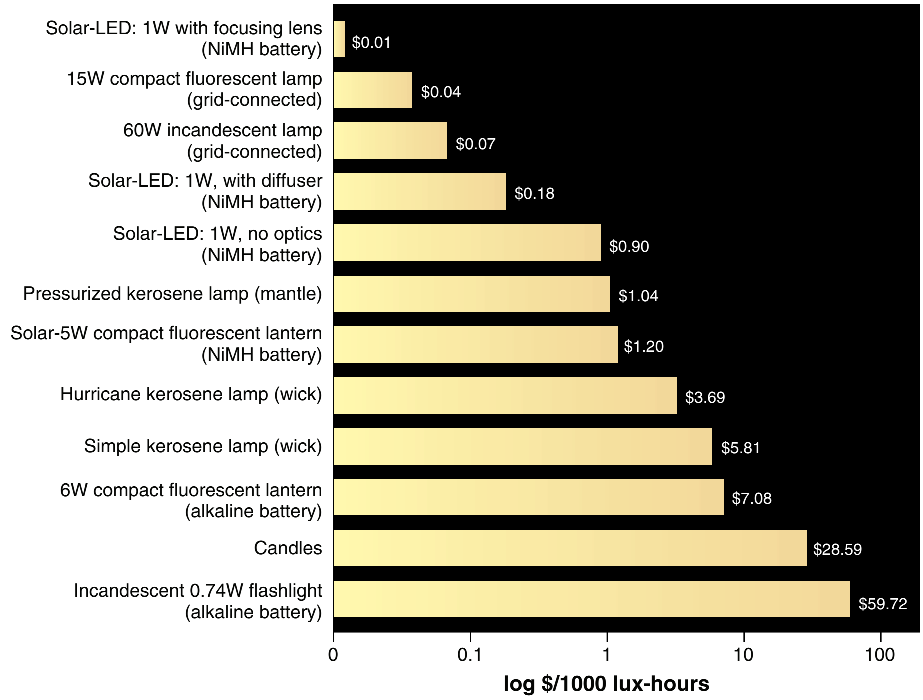
Commercially available 1-watt WLEDs require 80% less power than the smallest energy-efficient compact fluorescent lamps and can be run on AA batteries charged by a solar array the size of a paperback novel. Rapid efficiency gains have made such systems affordable (fig. S5). With long service life, direct current operation, ruggedness, portability, and ability to utilize inexpensive and readily available batteries, WLED lanterns are well suited for developing country applications. Early demonstrations of primitive WLED systems were well received in the developing world (*21*), and more advanced prototypes were later developed at Stanford University. When evaluated in terms of total cost of ownership (purchase plus operation), WLED systems emerge as the most cost-effective solution for off-grid applications (table S3). In fact, WLEDs can also provide very substantial savings when compared with the often inefficiently applied electric lighting in grid-connected homes (see SOM).

Entrepreneurs and charities have deployed relatively complex large-scale solar-fluorescent systems in the developing world with some success. But, at least partly because of cost, market penetration is only 0.1%. In the absence of a service infrastructure, these systems often fall into disrepair (*22*, *23*, *24*). Innovative financing and service strategies are now emerging.

Although less costly WLED systems are well suited for task- and narrow-area ambient lighting, these larger systems or solar-fluorescent lanterns certainly have an important role to play in meeting the broader demand for electricity and for wide-area lighting applications in households that can afford them.

Some have begun to cultivate the enormous potential for self-contained solar-WLED alternatives, which should come to market at a relatively affordable price of about US$25, without subsidy, and pay for themselves in 1 year or less (fig. S6). The fuel savings represent an ongoing annuity, equal to a month's income each year for the 1 billion people who live on less than $1/day.

Solutions to the problem of fuel-based lighting are emblematic of the notion that end-use energy efficiency is integral to providing energy services at least cost. As demonstrated in the case of lighting, attaining a higher standard of living does not require increased energy use. Yet, the specter of fuel-based lighting—linked tightly with energy security, equity, and development concerns—remains a largely unmet challenge for policy-makers. If current trends continue, lighting energy demand and greenhouse gas emissions will increase sharply as countries develop and replace a relatively small number of fuel-based lanterns with more and more grid-connected electric light (*25*, *26*). Or, with a reversal of the technical double standard seen prevailing since Edison's day we could see the use of WLEDs for illumination take hold first in the developing countries, where the need and potential benefits are greatest.



Total cost of illumination services. Costs include equipment purchase price amortized over 3 years, fuel, electricity, wicks, mantles, replacement lamps, and batteries. Performance characteristics of light sources vary; values shown reflect common equipment configurations (see table S3) and include dirt depreciation factors for fuel lanterns and standard service depreciation factors for electric light per Illuminating Engineering Society of North America. Assumptions are 4 hours/day operation over a 1-year period in each case, $0.1/kWh electricity price, $0.5/liter fuel price. NiMH, nickel metal hydride. (Range of market prices for kerosene shown in table S5.) We estimate an average of 11 liters (*1*) of lighting fuel per household per month; oberved values vary from 2 to 20 liters (table S4).

References and Notes

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Supporting Online Material
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Figs. S1-S6
Tables S1-S5
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Overview

To facilitate comparisons among alternative fuel and electric lighting strategies, we developed a standardized engineering-economic analysis methodology.[1] To fill gaps in the existing literature, we evaluated the photometric performance of fuel-based lanterns, and 1-watt white light-emitting diode (WLED) light sources, with and without optical control (figs. S1-4). We coupled total cost of ownership and illumination performance data for an array of electric lighting alternatives to generate a ranking of costs per unit of lighting service provided ($/1000lumen-hours or $/1000 lux-hours), as well as a payback-time analysis for the LED system compared to other systems (figs. S5-6 and tables S1-5). Our methodology for energy use analysis is described elsewhere (Mills 2005). This work contributes to the existing knowledge base, as estimates of energy use in the literature do not typically specify operating conditions or assumptions, and measurements of luminous flux often overlook the optical (in)efficiencies of fuel-based lamps or the potential impact of optics when used with WLEDs.

Light Output, Distribution, and Efficacy for Fuel-based and WLED Light Sources

Methods

The process of producing light in fuel-based lamps is predicated on the inefficient combustion of fuel and the consequent production of particulates, the burning of which emits light. We evaluated the geometry of light output (luminous flux) from fuel-based lanterns using a calibrated gonio-photometer (figs. S1-2) constructed and located at Lawrence Berkeley National Laboratory. We utilized a smaller, special-purpose gonio-photometer (also constructed and located at LBNL) to evaluate WLED sources. The analysis allows comparison of these potentially interchangeable light sources.

Gonio-photometry is an established method for evaluating modern electric light sources, and the resulting photometric data are readily available (Mills et al. 1997). The gonio-photometer progressively scans an operating light source in both the horizontal and vertical planes, providing quantitative analysis of light distribution (typically in units of candelas, cd) in various directions. The results are logged using an automated data acquisition system. Measurements are integrated to estimate total luminous flux. We complement these data with light-level measurements made using standard illuminance meters.

[1] More information here: http://eetd.lbl.gov/emills/PUBS/Fuel_Based_Lighting.html

complement these data with light-level measurements made using standard illuminance meters.

<u>Findings</u>

Candlepower distributions for a traditional fuel-based lantern, Lamp 1 (22mm flat wick), are shown in fig. S3a for the case with a clean glass chimney. Total luminous flux is 82 lumens, or a maximum of 9-10 candelas in the horizontal direction.[2] The distribution of light is reasonably constant in a given horizontal plane, as can be seen by comparing the various colored curves. The one exception is the view at 90 degrees, which—because the wick's narrow rectangular cross section is presented on edge—"sees" only one-half to two-thirds as much light. Due to interference by the large lamp base, the vertical flux is lowest in the first 50 degrees of view as the angle of view sweeps outwards from the bottom of the lamp. This is undesirable for horizontal tasks such as reading, which tend to be located in this sector. Vertical tasks receive the maximum amount of illumination.

After approximately 10 hours of normal operation, significant soiling accumulated on the inner surface of the lantern's chimney (especially at the shoulder), resulting in both lower overall luminous flux (52 lumens) as well as considerable non-uniformity depending on which radial angle the lamp is viewed from (fig. S3b).

Figs. S3c-d depict the clean-chimney performance as well as the above-mentioned performance-depreciation problem for a second traditional hurricane-style fuel lantern (Lamp 2) with a smaller (12mm) and less-clean-burning wick after only eight hours of operation. Note the highly asymmetrical light distribution resulting from obstructions integral to the lantern's design. Due to the large base below and metal hood above the chimney, there is no light emission above approximately +/-140 degrees or below +/-60 degrees in the vertical plane, which reduces the overall optical efficiency of the system given that much of the light produced by the flame is absorbed as it strikes the inner surfaces of the lantern's base and cap. Luminous flux was 48 lumens with a clean chimney (6-7 cd), falling to only 8 lumens (as low as 1 cd) as soot accumulated on the chimney. The "dent" in flux at 150 degrees (horizontal) is due to the vertical metal brackets on either side of the chimney.

Fig. S3e presents results for the simple oil lamp (4mm cylindrical wick), with a clean chimney. Measured luminous flux was 8 lumens, or 0.7 cd in the brightest direction. The original hand-blown chimney lacked the clarity of machine-made glass, due to bubbles and other imperfections. Measured transmission losses were significant at 27%. Due to the relatively narrow base, this lamp does a better job of delivering light to tasks at lower angles of view.

We also performed goniometric analysis for white LED sources. The use of optics is an important determinant of performance. Figs. S4a-b illustrate the extremes. Diffusers and

[2] To determine illuminance at points perpendicular to the light luminous flux, the measured candelas are divided by the square of the distance from the object (in meters for lux and in feet for footcandles). For this analysis, a distance of one meter is assumed.

other types of optics can be applied to yield light distributions anywhere between these two extremes. Plots show only one radial dimension, as these sources yield highly symmetrical light distribution patterns for a moderately efficient (25 lumens per watt) WLED with (inefficient) polycarbonate optics. Measurements for more efficient systems have yielded over 600 lux at 1 meter.

Field Measurements of Electrified Households in the Developing World

Using standard illuminance meters (WattStopper FX-200 Illuminometer), we measured light levels (lux) in electrified households in China. The combination of poor installation (distance from task), low-efficiency (inexpensive incandescent lamps operating less than 10 lumens/watt), soiling of lamps by wood smoke, and low coefficients of utilization (owing to woodsmoke-blackened walls and ceilings), translate into remarkably low delivered lighting services (lux levels) and disproportionately high electricity usage.

Typical homes we inspected in rural China utilized one to two 20W to 150W incandescent lamps and delivered lighting services ranging from 1 to 50 lux (compared to Western standards of 300 to 500 lux for many common tasks). In many parts of the rooms, levels of even 1 lux could not be registered. With WLEDs, significantly higher illuminance levels consistent with our lab tests were attained (over smaller areas) with only 1W of power input.

We observed similar problems and opportunities in non-residential settings. Our measurements in schools, shops, and monasteries revealed even more significant opportunities, owing to higher incandescent lamp wattages (typically 150W) and significantly longer hours of use in these contexts. The issue is particularly worrisome in the case of schools schools, where light levels varied by a factor of ten around the classroom and learning problems and eyestrain are correlated.

As the electricity generation mix in China is dominated by coal, and prices are moving towards market-based values, the potential impacts of WLEDs are substantial among electrified households there, and presumably elsewhere in the developing world.

Summary and Conclusions

Fuel-based lighting energy use and luminous flux vary considerably depending on the type of technology used and degree of chimney soiling. As an indication of the importance of independent testing of fuel-based lighting technologies, we found rated light output 40% lower than manufacturers' ratings and energy use 2.4 to 3 times higher (Mills 2005).

Our measurements of fuel-based lamps indicate that light distribution (and, by inference, illumination) is highly non-uniform in both the horizontal and vertical planes, i.e., depending on the angle of view. In contrast, modern electric light sources typically exhibit a very uniform distribution at any given angle in the horizontal plane. Illuminance is particularly poor for reading or other tasks on horizontal surfaces. It is relatively good for vertical tasks such as weaving.

Our estimates of useful illuminance on typical tasks show that the fuel-based lamps deliver between substantially sub-standard levels of illumination when compared with western standards. The intensity of flux deteriorates considerably from these already inadequate levels (up to 83%) as the chimney becomes soiled. In contrast, lumen depreciation in electric lighting systems is typically in the single-digit range after many months of operation.

While not quantified here, the potential energy, economic, and environmental[3] benefits of WLEDs applied in already electrified households and other building types appears to be substantial, with associated opportunities for increasing service levels and thus the quality of life.

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[3] Our environmental analysis focused on greenhouse gas emissions (carbon dioxide). The widespread use of batteries for lighting in the developing world presents a major additional environmental and economic dimension.

Supporting Figures

Fig S1. Gonio-photometer during measurement of electric table lamp.

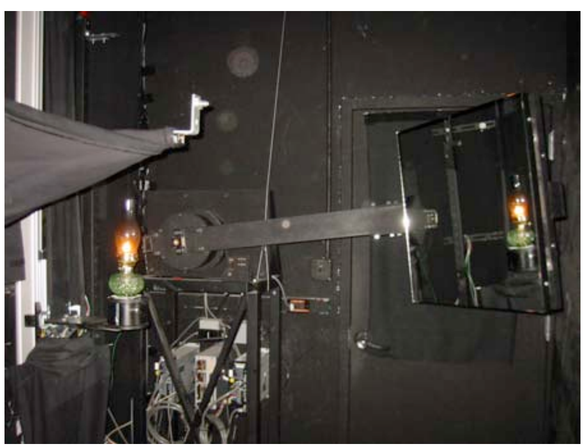

Fig S2. Gonio-photometer during measurements of kerosene lantern.

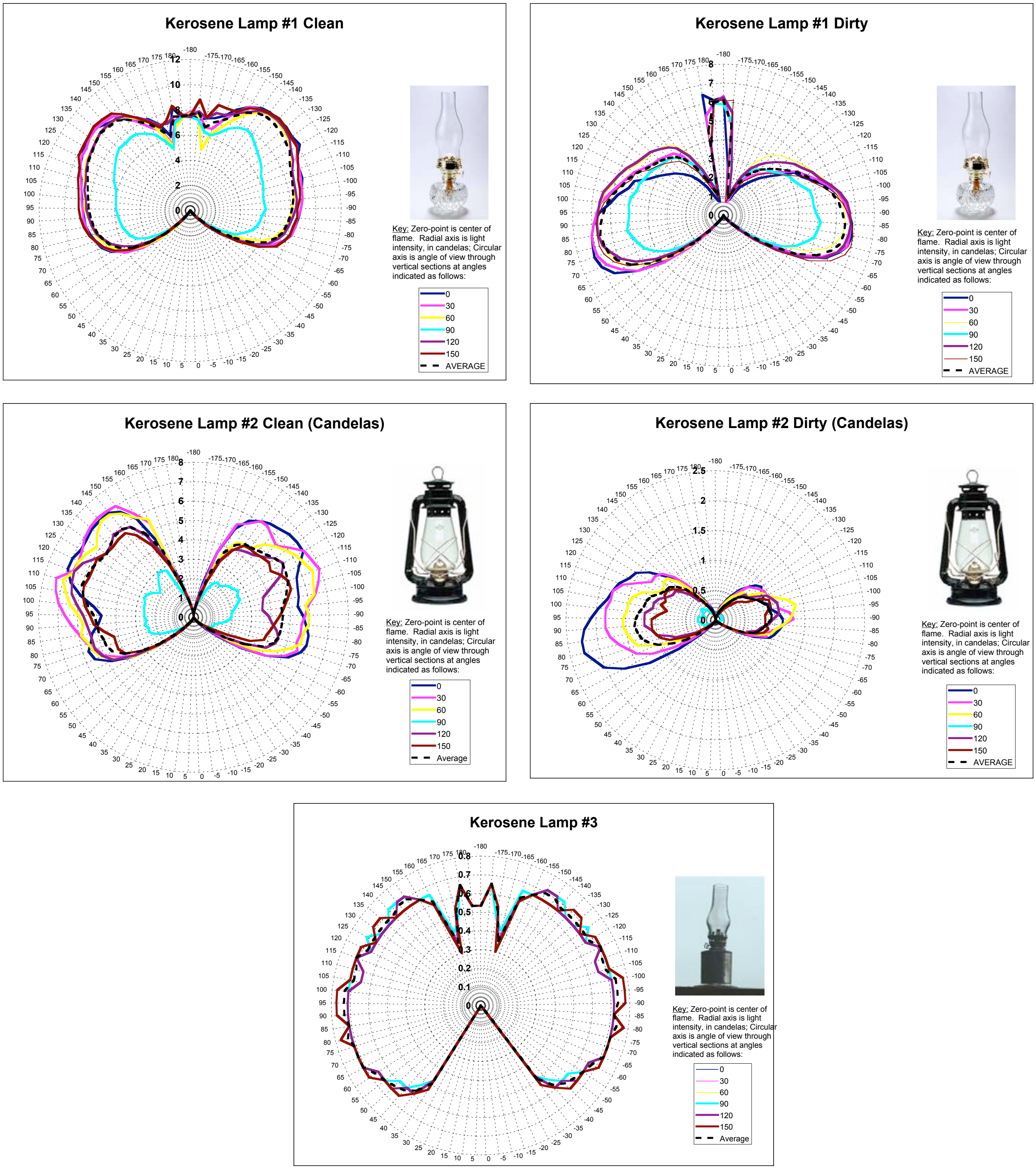

Figure S3a-e. Candlepower diagrams for typical kerosene lanterns. Goniophotometer measurements show strength and directionality of light emissions in the vertical plane and across various radial horizontal angles of view. Such analyses are routinely performed for electric lighting systems.

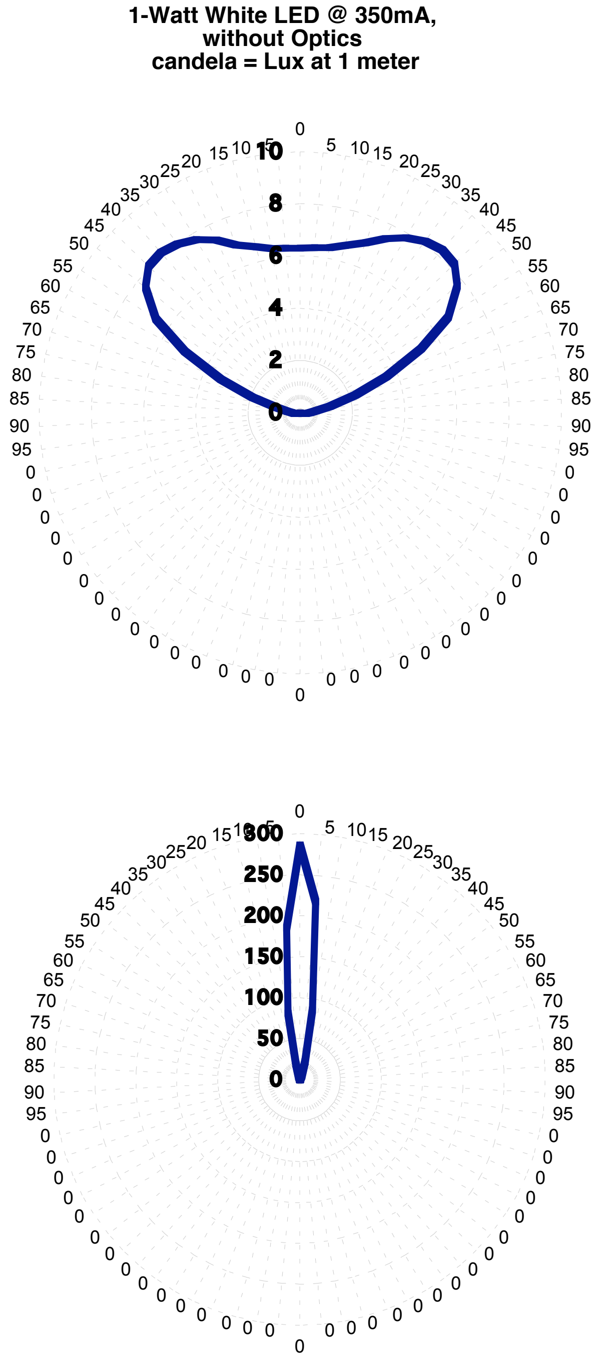

Figure S4a-b. Candlepower diagrams for 1W, 25lm white solid-state light sources (light-emitting diodes). Goniophotometer measurements indicate the strength and directionality of light emissions in the vertical plane and across various radial horizontal angles of view. The light source is identical in each panel (a) without and (b) with polycarbonate optical lens to gather and distribute light over narrow angle. Diffusers or other lens types yield an intermediary result between these two figures.

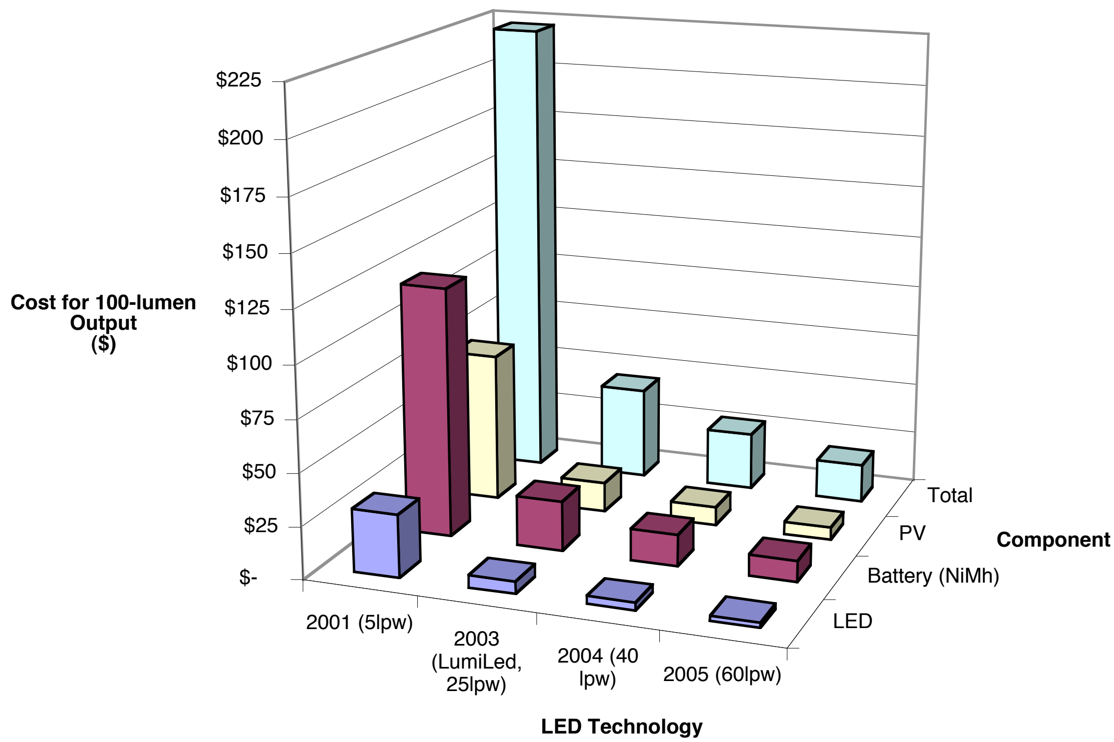

Figure S5. Effect of improving WLED efficiencies on photovoltaic and battery sizing and overall system cost. Standardized to 50-lumen output.

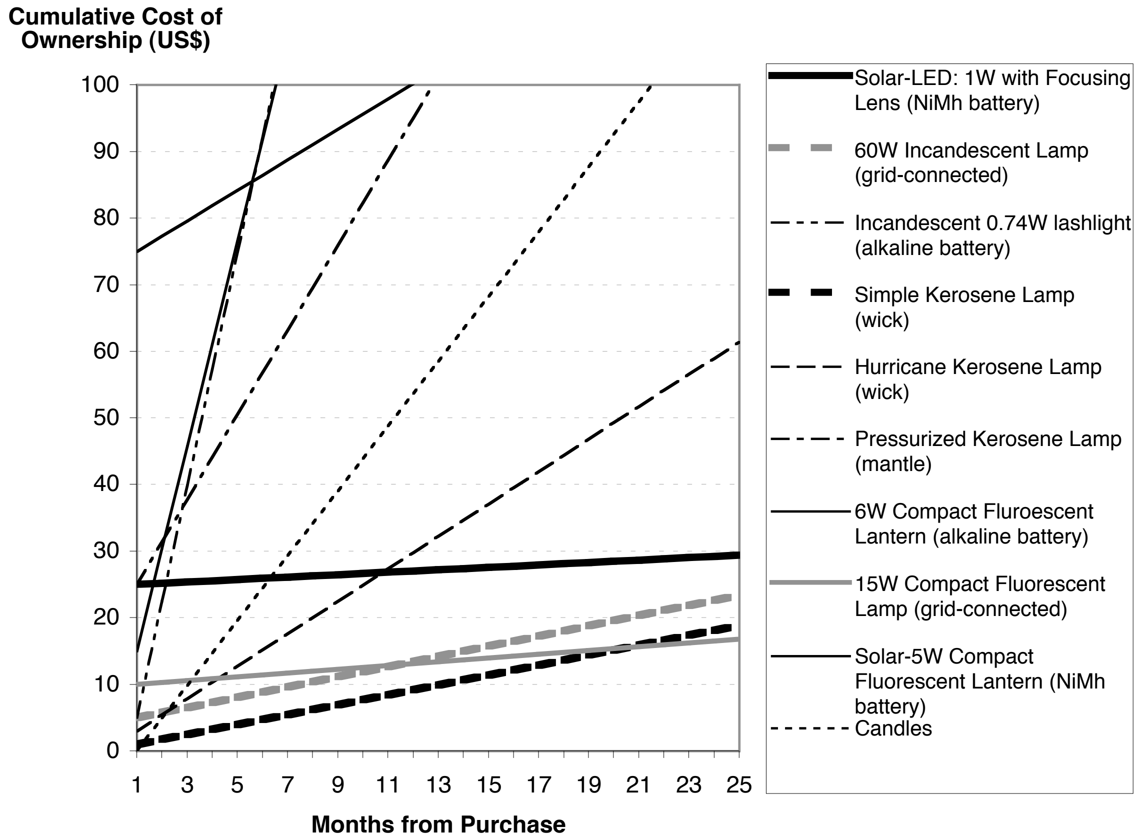

Figure S6. First costs (y-intercept) and cumulative operating costs (slope). Economic payback time (months) for WLED system (heavy black curve) occurs when heavy black curve crosses that of competing technology. Slope is proportional to operating cost (replacement batteries, lamps, candles, wicks, etc.) Curves for grid-connected sources shaded grey.

Supporting Tables

Table S1. Energy used for household fuel-based lighting in developing countries. To approximate the additional use of fuel by intermittently electrified households, as well as those without light in schools, workplaces, etc., we assume an effective un-electrified population of 2 billion. We take a kerosene lamp as the reference light source, with a rate of fuel consumption at 0.035 liters per hour, and a daily utilization rate of 4 hours. This is a proxy for a mix of lamp types, fuels, and range of utilization in practice. To approximate direct societal economic costs, we have excluded the effects of energy subsidies. Note: energy usage does not include evaporation from lanterns when notin use, which could be substantial.

Household lighting characteristics	
Population without electricity	2,000,000,000
People per un-electrified household	4
Unelectrified households	500,000,000
Fuel lamps per household	3.0
Number of lamps	1,500,000,000
Lamps per capita	0.75
Fuel consumption per lamp (liters per hour)	0.035
Average daily lamp use (hours per lamp)	4
Daily lamp-hours/capita	3.0
Annual energy use	
(liters kerosene)	76,650,000,000
(GJ)	2,793,892,500
(PJ)	2,794
[Mbod equivalent]	1.3
(MTOE)	65.6
Liters fuel per month per household	12.8
Liters fuel per month per capita	3.2
Cost comparision	
Cost of fuel-based lighting ($Billion/y)	38
Emissions comparison	
CO_2 emissions from fuel-based lighting (MT CO_2)	189
Comparative energy services and costs	
Energy services provided (1000 lumen-hours per lamp; 3 lamps per household and 4h/day operation)	
Fuel-based lighting (40-lumen lanterns)	175
Electric Lighting (60-watt lamps instead of fuel)	3942
Ratio:	23
Cost ($/year-household; all lamps)	
Electrified (IEA countries)	82
Fuel-based	77
Ratio:	0.9

Table S2. Equity considerations of fuel-based lighting: comparative performance of kerosene and electric lighting.

	White LED Lamp	Units	Ratio (fuel/LED)	Simple Hurricane Lamp	Units
Assumptions					
Energy price	0.10	$/kWh of electricity		0.5	$/liter of kerosene
Rate of energy consumption	1	Watt		0.035	liters/hour
Energy services provided	60	lumens	**0.67**	40	lumens
Carbon/energy	0.096	kgCO2/MJ	**0.76**	0.072	kgCO2/MJ
Energy Analysis					
Electricity	10.47	MJ/kWh			
Kerosene				36.45	MJ per liter of kerosene
Rate of energy use	0.01047	MJ/hour	**122**	1.27575	MJ/hour
Energy per unit of lighting service provided	0.2	MJ/klm-h	**183**	31.9	MJ/klm-h
Economic Analysis					
Energy price	9.55	$/GJ	**1.44**	13.72	$/GJ
Cost for equivalent lighting service	$0.0017	$/klm-h	**263**	$ 0.44	$/klm-h
Carbon/Service	0.02	kgCO2/klm	**138**	2.30	kgCO2/klm

Table S3. Comparative analysis of lighting systems for developing countries. Total cost of illumination services, including first costs and operation. Costs include initial purchase cost, fuel, electricity, wicks, mantles replacement lamps, and batteries. Performance characteristics of light sourc
price, $0.5/liter fuel price
household composition, lifestyle, relative fuel prices, and cultural preferences.

	60W Incandescent Lamp (grid-connected)	Incandescent 0.74W lashlight (alkaline battery)	15W Compact Fluorescent Lamp (grid-connected)	6W Compact Fluroescent Lantern (alkaline battery)	Solar-5W Compact Fluorescent Lantern (NiMh battery)	Candles	Simple Kerosene Lamp (wick)	Hurricane Kerosene Lamp (wick)	Pressurized Kerosene Lamp (mantle)	Solar-LED: 1W, no Optics (NiMh battery)	Solar-LED: 1W, with Dffuser (NiMh battery)	Solar-LED: 1W with Focusing Lens (NiMh battery)
Performance												
Rate of energy use (Watts or liters/hour)	60	0.74	15	6	6		0.01	0.035	0.10	1.0	1.0	1.0
Lamp, wick, or mantle service life (hours)	1000	15	5000	3000	3000	2.5	200	400	1000	50000	50000	50000
Replacement bulbs, wicks, or mantles (number per year)	1.5	97.3	0.29	0.49	0.49	584	7.3	3.7	1.5	0.00	0.00	0.00
Batteries	none	2 D Alkaline	none	4 D Alkaline	1 NiMh	none	none	none	none	3 AA NiMh	3 AA NiMh	3 AA NiMh
Replacement batteries (number per year)	0	360	0	365	0.73	0	0	0	0	2.190	2.190	2.190
Energy services provided												
Light output (lumens--lamp only)	792	3.8	873	131	213	10.0	7.8	40	400	60	60	60
Useful illumination (lux, including optical losses at typical working distance)	111	2.4	122	18	30	1.4	1.1	5.6	56	8	40	600
Efficiency (lumens/Watt)	13	5	58	22	36	0.2	0.08	0.11	0.80	60	60	60
First cost (lamp + fixture)	5	5	10	15	75	0.10	1	3	25	25	25	25
Annual Energy Consumption												
Electricity from grid (kWh)	88	0	22	0	0	0	0	0	0	0	0	0
Kerosene (liters)	0	0	0	0	0	0	15	51	148	0	0	0
Annual Operating Costs												
Energy	$ 8.76	$ -	$ 2.19	$ -	$ -	$ -	$ 7.30	$ 25.55	$ 74.22	$ -	$ -	$ -
Replacement batteries, wicks or mantles	$ -	$ 180.07	$ -	$ 182.50	$ 25.55	$ 58.40	$ 1.62	$ 3.65	$ 2.19	$ 2.19	$ 2.19	$ 2.19
Replacement bulbs	$ 0.44	$ 29.20	$ 1.17	$ 1.95	$ 1.95	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total	$ 9.20	$ 209.27	$ 3.36	$ 184.45	$ 27.50	$ 58.40	$ 8.92	$ 29.20	$ 76.41	$ 2.19	$ 2.19	$ 2.19
Operating cost per unit of service (1st cost amortized over three years)												
Cost of light ($/1000-lumen hours)	$ 0.01	$ 37.72	$ 0.00	$ 0.96	$ 0.09	$ 4.00	$ 0.78	$ 0.50	$ 0.13	$ 0.03	$ 0.03	$ 0.03
Cost of illumination ($/1000 lux-hours)	$ 0.06	$ 59.25	$ 0.02	$ 6.89	$ 0.63	$ 28.57	$ 5.60	$ 3.57	$ 0.93	$ 0.19	$ 0.04	$ 0.003
Operating cost per unit of service												
Light production ($/1000-lumen hours)	$ 0.008	$ 37.72	$ 0.003	$ 0.96	$ 0.09	$ 4.00	$ 0.78	$ 0.50	$ 0.131	$ 0.025	$ 0.025	$ 0.025
Index: CFL (grid) = 1.00	3	14,317	1	366	33	1,518	297	190	50	9	9	9
Illuminance ($/1000 lux-hours)	$ 0.06	$ 59.25	$ 0.02	$ 6.89	$ 0.63	$ 28.57	$ 5.60	$ 3.57	$ 0.93	$ 0.19	$ 0.04	$ 0.003
Index: CFL (grid) = 1.00	3	3,148	1	366	33	1,518	297	190	50	10.0	2.0	0.1
Total cost per unit of service (1st cost amortized over three years)												
Cost of light ($/1000-lumen hours)	$ 0.01	$ 38.02	$ 0.005	$ 0.99	$ 0.17	$ 4.00	$ 0.81	$ 0.52	$ 0.15	$ 0.12	$ 0.12	$ 0.12
Cost of illumination ($/1000 lux-hours)	$ 0.07	$ 59.72	$ 0.04	$ 7.08	$ 1.20	$ 28.59	$ 5.81	$ 3.69	$ 1.04	$ 0.90	$ 0.18	$ 0.01
Index: CFL (grid) = 1.00	1.8	1,593	1.0	189	32	762	155	99	28	24.0	4.8	0.3
1W LED (with optics) pack time,(years)	2.9	0.1	not applicable (lower 1st and operating cost)	0.1	0	0.4	3.6	0.8	-			
Carbon Dioxide Emissions per year (kg)	96	0	24	0	0		38	134	391	0	0	0

Assumptions for Table S3:

Lamp usage	4	hours/day
Household electricity price (from grid; rural)	0.10	$/kWh (World Bank 1996) can vary widely depending on local conditions).
D-cell Alkaline price	0.50	$ per battery (non-rechargable)
D-cell capacity	3.00	wh
AA-cell NiMh battery cost	1.00	$ per battery (rechargable)
AA NiMh battery life	500	cycles
Large NiMh solar lantern battery Life	500	cycles
CFL solar lantern NiMh replacement battery price	35	$ per battery
60W incandescent lamp price	0.30	$ per lamp
Simple kerosene wick price	0.22	$/length
Hurricane lamp wick price	1.00	$/length
Kerosene tie-on mantle price	1.50	$/mantle
Flashlight lamp ("bulb") wattage	0.74	2 D ind. cell flashlight; PR6; Philips
Flashlight lamp ("bulb") price	0.30	$ per lamp
Fixture price for grid-connected CFL or incandescent	5.00	($) simplest hard-wired connection or plug-in lamp
Compact fluorescent lamp price (grid-based)	4.00	$ per lamp
Replacement CFL price for solar lantern	4.00	$ per lamp
Fuel Price	0.5	$/liter
Lighting fuel (kerosene)	36.5	MJ/liter (45 MJ/kg; 0.81 kg/l)
Diesel w/v	0.87	kg/liter
Kerosene emissions factor	2.63	kg CO2/MJ
Electricity emissions factor	1100	grams CO2/kWh(e)

Notes & Sources:

- Most assumptions for electric light sources reflect high-quality western manufacturing (e.g. lamp life, efficacy); performance of some products can be much lo
- LED efficacies projected for end of 2005
- Lumen output values for standard electric sources are average mid-life values (including depreciation "maintenance factors" where applicable, based on IESNA Handbook Maintenance factor from fig. 6-40 IESNA handbook). Values for kerosene lamps are averages of tested levels.
- Derivation of lux values: for general electric sources, assumes even radiation in all directions from source 0.3 m high and 0.5 m from task (lux = 12% lumens). Room contributes another 2% from inter-reflections (3x3x2.5 m room with 50% surfaces). LED values are LBNL measurements, with varying degrees of optical control, 1 m from task. Kerosene measurements by LBNL goniophotometer at reading plane.
- Cost values shown are estimated final retail prices.

Table S4. Field reports of kerosene usage for lighting purposes.

Country	Usage (liters/month)	Source
Argentina	15.2–21.3	Kaufman et al (2000)
Bedoins	10-15	
Benin	3.0–11.7	Kaufman et al (2000)
Bhutan	5-20	Mills (2000)
Bolivia	5	Kaufman et al (2000)
Brazil	6.3	Costa (1997)
Burkina	12	Kaufman et al (2000)
Cape Verde	4-6	World Bank/UNDP/ESMAP 1990
China	7.3	UNIDO
Ecuador	13	ESMAP (1994, p. 107)
Ghana	4.8	Hagan and Addo (1994)
Guatemala	2	World Bank (2003)
Honduras	7.6	REPP
India	5	Laxmi et al (2003)
India	10	Power to Tackle Poverty
India	3.9	UNDP/ESMAP/World Bank (2003)
India (Rajastan)	5	Laxmi et al (2003)
Indonesia	16.4	Kaufman et al (2000)
Indonesia	15	Kaufman et al (2000)
Indonesia (Java)		
Low income	13.2	World Bank (1990)
Middle income	16.3	World Bank (1990)
High income	17.7	World Bank (1990)
Kenya	10.2	ESD
Nepal	2-8 liters/month (4.0 median)	Craine (private communication)
Nepal	4.25 (1 lamp)	LUTW
Peru	7.5	Kaufman et al (2000)
Sri	10.0–13.4	Kaufman et al (2000)
Tanzania	4-6	Ambeeka Energy Services (2000)
Togo	3.0–11.7	Kaufman et al (2000)
Zimbabwe	2.8	Kaufman et al (2000)

Table S5. Examples of domestic kerosene pricing around the world. Field reports of kerosene usage for lighting. Data reflect mix of currencies and years. Prices are those paid by households, with a mix of subsidies or taxes that vary from case to case. Other factors influencing price are proximity to urban centers; kerosene tends to become more expensive in remote areas and when purchased in small quantities. Note that all data predate the 2004-2005 oil price shock.

Country	Local price/liter	Currency	Exch/US$	**USD/liter**	Date	Source
Algeria	0.28	US$		**0.07**	Apr-99	USDOE/IEA (2001)
Argentina		US$		**0.44**	Dec-98	http://www.mof.gov.jm/taxmeasures/1999/consumption20tax.shtml
Argentina	1.77	US$		**0.47**	Apr-99	USDOE/IEA (2001)
Bangladesh	20	TK	55.66	**0.36**	May-04	http://www.thedailystar.net/2004/05/03/d40503011212.htm
Barbados	1	US$		**0.26**	Apr-99	USDOE/IEA (2001)
Bhutan	6	NU	46.94	**0.13**	1999	Mills (2000)
Bolivia		US$		**0.19**	Dec-98	http://www.mof.gov.jm/taxmeasures/1999/consumption20tax.shtml
Bolivia	0.72	US$		**0.19**	Apr-99	USDOE/IEA (2001)
Brazil	0.85	R	2.7385	**0.31**	May-97	Costa (1997)
Brazil	0.87	US$		**0.23**	Apr-99	USDOE/IEA (2001)
Cambodia		US$		**0.33**	1999	Mills (2000)
Chad	270	CFAF	506	**0.53**	Jun-09	World Bank
Chile	0.97	US$		**0.26**	Apr-99	USDOE/IEA (2001)
China	3.213	CNY	8.27	**0.39**	Jun-09	Jones et al
Columbia	0.83	US$		**0.22**	Apr-99	USDOE/IEA (2001)
Costa Rica	0.84	US$		**0.22**	Apr-99	USDOE/IEA (2001)
Cuba	0.32	US$		**0.08**	Apr-99	USDOE/IEA (2001)
Dominican Republic	1.16	US$		**0.31**	Apr-99	USDOE/IEA (2001)
Ecuador	15	S	25250	**0.00**	Jun-09	UNDP/ESMAP
El Salvador	0.89	US$		**0.24**	Apr-99	USDOE/IEA (2001)
Ethiopia				**0.38**	2005	B. Bayissa (personal communication)
Ghana		US$		**0.19**	1990	Hagan and Addo (1994)
Grenada	1.14	US$		**0.30**	Apr-99	USDOE/IEA (2001)
Guatemala	0.82	US$		**0.22**	Apr-99	USDOE/IEA (2001)
Guyana	0.71	US$		**0.19**	Apr-99	USDOE/IEA (2001)
Haiti	13.6	Gourdes	36.7	**0.37**	Jan-02	http://www.haitiprogres.com/2003/sm030108/eng01-08.html
Haiti	1.08	US$		**0.29**	Apr-99	USDOE/IEA (2001)
Haiti (black mkt)	27	Gourdes	36.7	**0.73**	Jan-02	http://www.haitiprogres.com/2003/sm030108/eng01-08.html
Honduras	13.73	Lps	12.76	**1.08**	Jul-97	http://www.marrder.com/htw/jul97/business.htm
Honduras	0.91	US$		**0.24**	Apr-99	USDOE/IEA (2001)
Hong Kong	1.45	US$		**0.38**	Apr-99	USDOE/IEA (2001)
India (actual)	16.54	Rs	43.5	**0.38**	Feb-03	Market price: http://www.rediff.com/money/2003/feb/19lpg.htm
India (black mkt)	20	Rs	43.5	**0.46**	Jul-04	Black Market http://www.deccanherald.com/deccanherald/july052004/d7.asp
India (subsidized)	17.55	Rs	43.5	**0.40**	Feb-03	Subsidized price: http://www.rediff.com/money/2003/feb/19lpg.htm
Indonesia	1000	Rp	8734	**0.11**	Jun-01	http://www.kompas.com/kompas-cetak/0106/21/ENGLISH/gove.htm
Jamacia	1.05	US$		**0.28**	Apr-99	USDOE/IEA (2001)
Jamacia				**0.44**	Dec-98	http://www.mof.gov.jm/taxmeasures/1999/consumption20tax.shtml
Kenya				**0.41**	1,997	ESN: http://www.esd.co.uk/downloads/
Kuwait	0.05	US$		**0.01**	Apr-99	USDOE/IEA (2001)
Liberia				**0.73**	2000	http://allafrica.com/stories/200009300011.html
Libya	0.11	US$		**0.03**	Apr-99	USDOE/IEA (2001)
Madagascar	160		635	**0.25**	May-84	World Bank (1987)
Myanmar	2.6	Kyats	6.42	**0.40**	Jan-05	http://www.ibiblio.org/obl/docs3/BNI2005-01-18.htm
Nepal	28	NRs	70	**0.40**	Apr-03	http://www.worldbank.org.np/WBSITE/EXTERNAL/COUNTRIES/SOUTHASIAEXT/NEPALEXTN/0,,contentMDK:20191793~pagePK:141137~piPK:217854~theSitePK:223555,00.html
Nepal	2	US$	1	**2.00**		Craine (n/d) -- remote locations
Nicaragua	0.97	US$		**0.26**	Apr-99	USDOE/IEA (2001)
Nicaragua				**0.78**	Jun-09	Albert et al.1997
Niger	160	CFAF	470	**0.34**	Jan-94	World Bank (1994)
Nigeria	65	N	131.88	**0.49**	Nov-04	http://www.afrika.no/Detailed/6601.html
Pakistan	19	RS	60	**0.32**	Jan-02	
Panama	0.97	US$		**0.26**	Apr-99	USDOE/IEA (2001)
Paraguay	1.04	US$		**0.27**	Apr-99	USDOE/IEA (2001)
Peru	0.91	US$		**0.24**	Apr-99	USDOE/IEA (2001)
Peru				**0.29**	Dec-98	http://www.mof.gov.jm/taxmeasures/1999/consumption20tax.shtml
Philippines	11	Peso	52.64	**0.21**	Mar-00	http://www.ibon.org/news/if/00/13.htm
Qatar	0.42	US$		**0.11**	Apr-99	USDOE/IEA (2001)
Saudi Arabia	0.44	US$		**0.12**	Apr-99	USDOE/IEA (2001)
Sri Lanka	24	SLRs	97	**0.25**	Feb-03	http://www.dailynews.lk/2003/02/14/new13.html
Suriname	1.36	US$		**0.36**	Apr-99	USDOE/IEA (2001)
Syria	8	Pounds	41.79	**0.19**	May-02	http://www.jordanembassyus.org/08172001001.htm
Tanzania				**0.50**	2000	Ambeeka Energy Services (2000)
Thailand	15		38.5	**0.39**	Jun-09	http://www.eppo.go.th/encon/encon-D07-PV-Final.doc
Trinidad				**0.18**	Dec-98	http://www.mof.gov.jm/taxmeasures/1999/consumption20tax.shtml
Trinidad and Tobagc	0.69	US$		**0.18**	Apr-99	USDOE/IEA (2001)
United Arab Emirate	0.79	US$		**0.21**	Apr-99	USDOE/IEA (2001)
Uruguay	1.51	US$		**0.40**	Apr-99	USDOE/IEA (2001)
US (New York)	0.5	USD	1	**0.50**	Apr-03	http://www.nyserda.org/nyepg.html
Venezuela	0.35	US$		**0.09**	Apr-99	USDOE/IEA (2001)
Zimbabwe	1.00	US$	1	**1.00**	Apr-02	Private Communication, Lasten Mika, Energy Technology Institute.

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Enhanced:
ENVIRONMENT:
The Specter of Fuel-Based Lighting

Evan Mills [HN10] *

Thomas Edison's seemingly forward-looking statement that "we will make electricity so cheap that only the rich will burn candles" [HN1] (1) was true for the industrialized world, but it did not anticipate the plight of 1.6 billion people (2)--more than the world's population in Edison's time--who more than a century later still lack access to electricity (see figure, this page). While electricity was becoming available in the wealthier countries, leaders of the oil industry (3, 4) promoted lighting-oil products in China and elsewhere. The legacy of costly and low-grade lighting for the world's poor remains. For those without access to electricity, lighting is derived from a diversity of sources, including kerosene, diesel, propane, biomass, candles, and yak butter. Many of the 35 million people living in camps for refugees and internally displaced people have no light at all.

Throughout the developing world, 14% of urban households and 49% of rural households were without electricity as of the year 2000 (2). [HN2] In extreme cases, e.g., Ethiopia and Uganda, only ~1% of rural households are electrified (5). An unknown additional number of people have intermittent access to electricity in their homes or lack it altogether in their workplaces, markets, schools, or clinics (6). The number and proportion of people lacking electricity is growing in sub-Saharan Africa and parts of Latin America and the Caribbean, the Middle East, and South Asia (7). Population growth, stalling rates of electrification, and declining household sizes (8) [HN3] exacerbate the problem. The number of people without access to electricity globally is projected to decline at only 0.4%/year over the next 3 decades (2).

Illumination is one of the core end-use energy services sought by society and is today obtained by some at efficiencies on the order of 100 lumens per watt and by others at well below 1 lumen per watt (9). Compounding this disparity, the least efficient sources also deliver less--and less uniform--light: A simple wick lantern provides about 1 lux (lumens/m^2) at 1 meter from the source, compared with levels on the order of 500 lux routinely provided in industrialized countries (figs. S1 to S3).

Although the energy performance of individual fuel-based light sources [HN4] has been analyzed previously (9, 10), the global dimensions have not been quantified. We estimate that fuel-based lighting is responsible for annual energy consumption of 77 billion liters of fuel worldwide (or 2800 petajoules, PJ), at a cost of $38 billion/year or $77 per household (table S1). This equates to 1.3 million barrels of oil per day, on a par with the total production of Indonesia, Libya, or Quatar, or half that of prewar Iraq. Consumption of lighting fuel is equivalent to 33% of the total primary energy (electricity plus fuel) used for household lighting globally and 12% of that across all lighting sectors (11). [HN5]

Used 4 hours a day, a single kerosene lantern [HN6] emits over 100 kg of the greenhouse gas carbon dioxide into the atmosphere each year. The combustion of fuel for lighting consequently results in 190 million metric tonnes per year of carbon dioxide emissions, equivalent to one-third the total emissions from the U. K.

Although about one in four people obtain light exclusively from fuel, representing about 17% of global lighting energy costs, they receive only 0.1% of the resulting lighting energy services (lumen hours). Despite the paucity of lighting services obtained, individual unelectrified households in the developing world spend a comparable amount of money on illumination as do households in the industrialized world.

Fuel-based lighting embodies enormous economic and human inequities. The cost per useful lighting energy services ($/lux-hour of light, including capital and operating costs) for fuel-based lighting is up to ~150 times that for premium-efficiency fluorescent lighting (see figure, next page). The total annual light output (about 12,000 lumen-hours) from a simple wick lamp is equivalent to that produced by a 100-watt incandescent bulb in a mere 10 hours.

By virtue of its inefficiency and poor quality, fuel-based light is hard to work or read by, poses fire and burn hazards, and compromises indoor air quality. Women and children typically have the burden of obtaining fuel (12, 13). Availability of lighting is linked to improved security, literacy, and income-producing activities in the home (14). [HN7] Fuel prices can be highly volatile (15), and fuels are often rationed, which leads to political and social unrest, hoarding, and scarcity.

Although sometimes driven by good intentions such as reducing demand for fuel wood, fuel subsidies divert public sector funds from other uses. In India, where nearly 600 million people are without electricity, kerosene and liquid propane gas subsidies are of the same magnitude as those for education (16). Subsidies also create price distortions that discourage conservation and encourage dangerous and polluting fuel adulteration in the domestic and transport sectors (17, 18).

Tailor working by candlelight in an "electrified" village in India.

CREDIT: EVAN MILLS

Centralized rural electrification has its own problems, not the least of which is the cost of distribution in rural areas with low load densities, coupled with the high capital costs and low efficiencies associated with thermal power generation. Power theft levels reach 40% in some countries (2).

Off-Grid Solid-State Lighting: An Opportunity for Technological Leapfrogging

As they modernize, developing countries can select better technologies and in so doing surpass levels of efficiency typical of industrialized countries (19). The latest improvement in lighting energy efficiency is the solid-state white light-emitting diode (WLED) [HN8] (20), distinguished from other lighting technologies by a continuing trend toward increasing light output, declining costs per unit of output, and rising efficiencies.

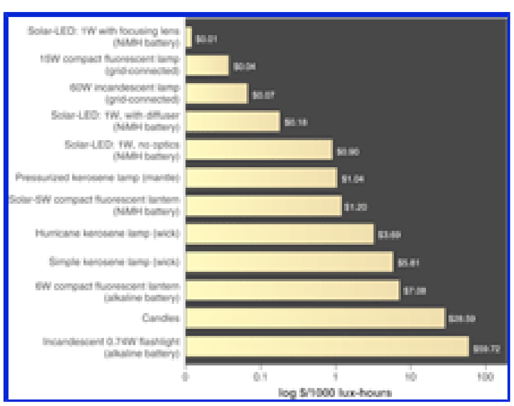
WLED technologies provide more and better illumination (with easier optical control) than do fuels (fig. S4), dramatically reducing operating costs (table S2) and greenhouse gas emissions, while increasing the quality and quantity of lighting services. Efficiencies of only five delivered lumens per watt in the mid-1990s are moving toward 100 lumens per watt (compared with 0.1 lumens per watt for a flame-based lantern). Relative light output (assuming 1-watt WLEDs) would be 5 lumens, 100 lumens, and 40 lumens, respectively. Coupled with inexpensive diffusers or optics, today's best WLEDs deliver 10 to 100 times as much light to a task as do traditional fuel-based lanterns.

Commercially available 1-watt WLEDs require 80% less power than the smallest energy-efficient compact fluorescent lamps and can be run on AA batteries charged by a solar array the size of a paperback novel. Rapid efficiency gains have made such systems affordable (fig. S5). With long service life, direct current operation, ruggedness, portability, and ability to utilize inexpensive and readily available batteries, WLED lanterns are well suited for developing country applications. Early demonstrations of primitive WLED systems were well received in the developing world (21), and more advanced prototypes were later developed at Stanford University. When evaluated in terms of total cost of ownership (purchase plus operation), WLED systems emerge as the most cost-effective solution for off-grid applications (table S3). In fact, WLEDs can also provide very substantial savings when compared with the often inefficiently applied electric lighting in grid-connected homes (see SOM). [HN9]

Entrepreneurs and charities have deployed relatively complex large-scale solar-fluorescent systems in the developing world with some success. But, at least partly because of cost, market penetration is only 0.1%. In the absence of a service infrastructure, these systems often fall into disrepair (22, 23, 24). Innovative financing and service strategies are now emerging.

Although less costly WLED systems are well suited for task- and narrow-area ambient lighting, these larger systems or solar-fluorescent lanterns certainly have an important role to play in meeting the broader demand for electricity and for wide-area lighting applications in households that can afford them.

Some have begun to cultivate the enormous potential for self-contained solar- WLED alternatives, which should come to market at a relatively affordable price of about US$25, without subsidy, and pay for themselves in 1 year or less (fig. S6). The fuel savings represent an ongoing annuity, equal to a month's income each year for the 1 billion people who live on less than $1/day.



Total cost of illumination services. Costs include equipment purchase price amortized over 3 years, fuel, electricity, wicks, mantles, replacement lamps, and batteries. Performance characteristics of light sources vary; values shown reflect common equipment configurations (see table S3) and include dirt depreciation factors for fuel lanterns and standard service depreciation factors for electric light per Illuminating Engineering Society of North America. Assumptions are 4 hours/day operation over a 1-year period in each case, $0.1/kWh electricity price, $0.5/liter fuel price. NiMH, nickel metal hydride. (Range of market prices for kerosene shown in table S5.) We estimate an average of 11 liters (1) of lighting fuel per household per month; oberved values vary from 2 to 20 liters (table S4).

Solutions to the problem of fuel-based lighting are emblematic of the notion that enduse energy efficiency is integral to providing energy services at least cost. As demonstrated in the case of lighting, attaining a higher standard of living does not require increased energy use. Yet, the specter of fuel-based lighting--linked tightly with energy security, equity, and development concerns--remains a largely unmet challenge for policy-makers. If current trends continue, lighting energy demand and greenhouse gas emissions will increase sharply as countries develop and replace a relatively small number of fuel-based lanterns with more and more grid-connected electric light (25, 26). Or, with a reversal of the technical double standard seen prevailing since Edison's day we could see the use of WLEDs for illumination take hold first in the developing countries, where the need and potential benefits are greatest.

References and Notes

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The author is at the U.S. Department of Energy's Lawrence Berkeley National Laboratory, MS 90-4000, Berkeley, CA 94720, USA. E-mail: emills@lbl.gov

HyperNotes
Related Resources on the World Wide Web

General Hypernotes

Dictionaries and Glossaries

An energy glossary is provided by the Energy Information Administration of the U.S. Department of Energy (DOE).

A glossary is included in the Users' Guide to Off-Grid Energy Solutions.

Web Collections, References, and Resource Lists

Eldis is a gateway to development information that provides summaries, resource guides, and links to online documents and related Web sites.

The Development Gateway is a resource maintained to exchange knowledge related to key issues in development.

The World Energy Council provides a collection of Internet links.

The Lawrence Berkeley National Laboratory's Energy Crossroads is a collection of energy-efficiency resources on the World Wide Web.

Lighting Crossroads, a collection of pointers to energy-efficient lighting resources on the Internet, is provided by the International Association for Energy-Efficient Lighting.

Sandia National Laboratories provides a collection of Internet links on solid-state lighting.

Online Texts and Lecture Notes

The United Nations Development Programme offers a resource page on energy for sustainable development. A collection of Internet links is provided.

The World Bank offers a resource page on energy issues. The World Bank's Energy Sector Management Assistance Programme is a global technical assistance program to developing countries on sustainable energy development. The World Bank's Asia Alternative Energy Program provides information on the Quality Program for Photovoltaics and the Energy, Poverty, and Gender Program, as well as a collection of related Internet links.

The Sustainable Development Department of the U.N. Food and Agriculture Organization (FAO) provides a resource section on energy and environmental technology.

The Light Up The World Foundation, established by D. Irvine-Halliday, brings lighting solutions to people in remote areas of developing countries. A collection of publications is provided.

The Solar Electric Light Fund (SELF) is a non-profit charitable organization founded in 1990 to promote, develop, and facilitate solar rural electrification. A collection of links and resources is provided.

D. M. Kammen, Renewable and Appropriate Energy Laboratory, University of California, Berkeley, makes available lecture notes for a course on energy and society.

The Users' Guide to Off-Grid Energy Solutions is an interactive guidebook that includes a section on lighting. A collection of Internet links is provided.

E. F. Schubert, Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, maintains a Light-Emitting Diodes (LED) Web site. A short course on LEDs and solid state lighting is offered.

Sandia National Laboratories offers information about solid-state lighting. A collection of review articles and other resources are provided.

General Reports and Articles

This issue of *Science* has a Review by E. F. Schubert and J. K. Kim titled "Solid-state light sources getting smart" (*20*).

The International Energy Initiative makes available in PDF format the contents of its journal *Energy for Sustainable Development*. The December 2004 issue was a special issue on power sector reform and its impact on the poor.

The Light Up The World Foundation makes available in PDF format a September 2002 *IEEE Spectrum* article by G. Zorpette titled "Let there be light."

The December 2001 issue of *Physics Today* had an article by G. Craford, A. Duggal, and R. Haitz titled "The promise and challenge of solid-state lighting."

The Energy Group, Princeton Environmental Institute, makes available in PDF format the 1985 *Ambio* article by J. Goldemberg, T. B. Johansson, A. K. N. Reddy, and R. H. Williams titled "Basic needs and much more with one kilowatt per capita" (*19*).

The 1997 book *Environment, Energy, and Economy: Strategies for Sustainability*, edited by Y. Kaya and K. Yokobori, is made available by the United Nations University Press.

Numbered Hypernotes

1. **History of lighting.** A timeline of lighting technology with links to articles is provided by Wikipedia. The About Inventors Web site offers articles about Edison's inventions and the history of lighting. Sandia National Laboratories offers a condensed history of lighting. The November-January 2000 issue of *ElectroLink Magazine* had an article by P. Kilby titled "The age of light: The first century." The Smithsonian National Museum of American History offers a presentation titled "Lighting a revolution."

2. **Electricity in the developing world.** The chapter on energy and poverty of the *World Energy Outlook 2002* (*2*) is made available in PDF format by the International Energy Agency. The December 2004 issue of *Energy for Sustainable Development* had an introductory overview by S. Karekezi, J. Kimani, R. Kozulj, and N. Di Sbroiavacca on electricity in the developing world (*7*) and an article by S. Karekezi and J. Kimani titled "Have power sector reforms increased access to electricity among the poor in East Africa?" (*5*). The World Energy Council makes available a 1999 report titled *The Challenge of Rural Energy Poverty in Developing Countries*. "Meeting the challenge: Rural energy and development for two billion people" is a policy paper available from the Rural and Renewable Energy Thematic Group of the World Bank.

3. **Effects of households.** J. Liu, Department of Fisheries and Wildlife, Michigan State University, makes available in PDF format the 30 January 2003 *Nature* article by J. Liu, G. C. Daily, P. R. Ehrlich, and G. W. Luck titled "Effects of household dynamics on resource consumption and biodiversity" (*8*), as well as the related News and Views article by N. Keilman titled "The threat of small households." Michigan State University issued a 12 January 2003 press release about this research titled "Peoples' household dynamics crucial to biodiversity."

4. **Fuel-based lighting.** The 1988 report by R. van der Plas and A. B. de Graaff titled "A comparison of lamps for domestic lighting in developing countries" (*9*) is available in PDF format from the World Bank. The World Bank Energy Web site makes available in PDF format a July 1998 Energy Issues paper by W. M. Floor and R. J. van der Plas titled "Rural lighting services. A comparison of lamps for domestic lighting in developing countries." The Energy Research Centre of the Netherlands makes available a 1998 article by F. D. J Nieuwenhout, P. J. N. M. van de Rijt, E. J. Wiggelinkhuizen, and R. J. van der Plas titled "Rural lighting services: A comparison of lamps for domestic lighting in developing countries." The May 1994 issue of *Energy for Sustainable Development* had an article by G. S. Dutt titled "Illumination and sustainable development: Part I: Technology and economics" (*10*).

5. **Global costs of fuel-based lighting.** IAEEL makes available a February 1999 newsletter article by E. Mills titled "Fuel-based light: Large CO_2 source." E. Mills makes available in PDF format a 2002 conference paper (and the slide presentation) titled "The $230-billion global lighting energy bill" (*11*). The February-April 2001 issue of *ElectroLink Magazine* had an article "Tallying the costs of global lighting."

6. An entry on the **kerosene lamp** is included in Wikipedia. The Light Up The World Foundation offers a presentation titled "The global challenge—Reducing dependence on kerosene for lighting in the developing world." V. Quaschning's renewable energy Web site provides information on specific carbon dioxide emissions of various fuels (including kerosene).

7. **The personal burden of fuel-based energy.** The September 2003 issue of *Energy for Sustainable Development* was a special issue on gender and energy; included was an article by S. Batliwala and A. K.N. Reddy titled "Energy for women and women for energy (engendering energy and empowering women)" (*12*). The March 2003 issue of *Energy for Sustainable Development* had an article by V. Laxmi, J. Parikh, S. Karmakar, and P. Dabrase titled "Household energy, women's hardship and health impacts in rural Rajasthan, India: Need for sustainable energy solutions" (*13*). The World Bank makes available a 2001 report titled "Peri-urban electricity consumers--a forgotten but important group: What can we do to electrify them?" (*14*).

8. **Solid-state white light-emitting diode (WLED) lighting.** National Public Radio's Living on Earth makes available a presentation titled "LEDs: The future of light." The Lighting Research Center, Rensselaer Polytechnic Institute, provides an introduction to solid state lighting. DOE's Energy Efficiency and Renewable Energy Web site includes a resource section on solid state lighting. The October 2003 issue

of *OE Magazine* had an article by T. Taguchi titled "Light gets solid." The vol. 3, no. 4, 1998 issue of the newsletter *Lighting Futures* had an article by A. Bierman titled "LEDs: From indicators to illumination?" Sandia National Laboratories offers a FAQ on solid-state lighting with an entry titled "How do you produce white light using LEDs?"

9. **WLEDs for the developing world.** The Light Up The World Foundation provides an introduction to WLEDs and summarizes the benefits of WLEDs; also available in PDF format is a presentation titled "Solid state light for developing countries." The National Renewable Energy Laboratory makes available in PDF format a meeting presentation titled "Solid state lighting for human development" from the 2003 National Center for Photovoltaics and Solar Program review meeting. The Stanford Graduate School of Business makes available a June 2003 article titled "LED lamps light the way." IGNITE Innovations, a 'spin-off' from Stanford University, provides information about the IGNITE Light, a WLED that is powered by batteries charged by solar power. The Manitoban student newspaper had a 26 February 2003 article by C. Evans titled "Lighting up in Nepal: White-light-emitting-diode technology." *IEEE Spectrum* Online makes available a December 2004 article by P. Fairley titled "Lighting up the Andes."

10. **Evan Mills** is in the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory.

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The editors suggest these related resources at *Science*:

- **Solid-State Light Sources Getting Smart**
  E. Fred Schubert and Jong Kyu Kim
  Science 27 May 2005: 1274-1278
  [Abstract] [Full Text] [PDF]

Volume 308, Number 5726, Issue of 27 May 2005, pp. 1263-1264.

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