ENVIRONMENT

The Specter of Fuel-Based Lighting

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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.

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.

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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

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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.

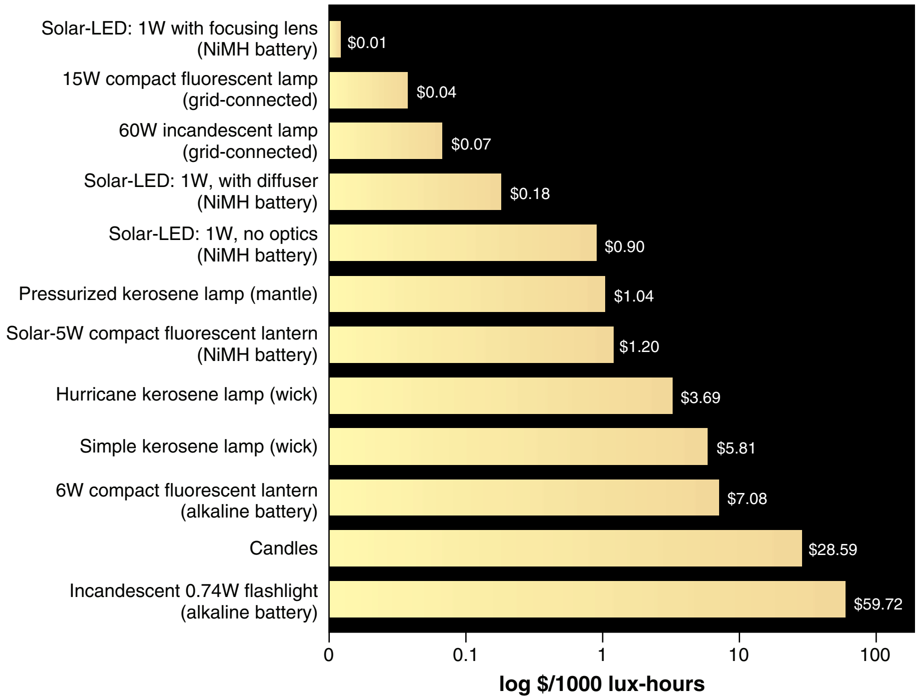
Commercially available 1-watt WLEDs require 80% less power than the smallest energy-efficient compact fluorescent lamps and can be run on AA batteries charged by a solar array the size of a paperback novel. Rapid efficiency gains have made such systems affordable (fig. S5). With long service life, direct 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).

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