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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.

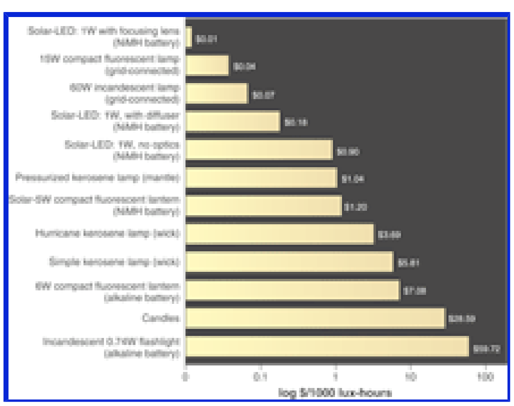
WLED technologies provide more and better illumination (with easier optical control) than do fuels (fig. S4), dramatically reducing operating costs (table S2) and greenhouse gas emissions, while increasing the quality and quantity of lighting services. Efficiencies of only five delivered lumens per watt 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.

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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]

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