The $230-billion Global Lighting Energy Bill*

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ABSTRACT

This paper presents the first global estimate of lighting energy use, costs, and associated greenhouse-gas emissions. Based on a compilation of estimates for 41 countries representing approximately 63% of the world's population, we develop a model for predicting lighting electricity use for other countries where data are lacking. The corresponding lighting-related electricity production for the year 1997 is 2016 TWh (21103 Petajoules), equal to the output of about 1000 electric power plants, and valued at about $185 billion per year. Global lighting electricity use is distributed approximately 28% to the residential sector, 48% to the service sector, 16% to the industrial sector, and 8% to street and other lighting. The corresponding carbon dioxide emissions are 1775 million metric tonnes per year. Lighting electricity demand in the 23 International Energy Agency (IEA) countries represents approximately half of the world's total lighting use. Our parallel examination of global fuel-based household lighting suggests that it represents an amount of primary energy of 3600 PJ ($48 billion), equal to 115% of that used to provide household electric lighting in all IEA countries, and 244 MT carbon dioxide emissions. Although one in three people obtain light with kerosene and other fuels, representing about 20% of global lighting costs, they receive 0.2% of the resulting lighting energy services. While collecting end-use energy data is arguably not a high national priority in most countries, this lack of attention is particularly problematic in this instance given that lighting is usually a preferred target for energy savings campaigns and policies. Without such data, precise scenarios of future lighting electricity demand cannot be developed. Improved work in this area seems merited given our estimated global savings potential of $75 to 115 billion/year.

1 GLOBAL ELECTRIC LIGHTING

1.1 APPROACH & METHODOLOGY

In this paper, we develop the first global estimate of electricity demand, cost, and greenhouse-gas emissions for lighting. We approached this problem by creating a new database of national lighting energy use estimates. A special focus on the 23 International Energy Agency (IEA) countries[1] enables us to put lighting energy use for industrialized countries in context with global demand.

Our database currently contains electric lighting energy use estimates for 41 countries representing 3.7 billion people (63% of the world's population and 81% of the PPP-corrected world GDP in 1997). We have focused separately on each major end-use sector (residential, service, industry, and street/other lighting) (Figure 1 and Table 1).

In cases where multiple estimates existed for a given country, we tabulated them and selected the most reliable estimate for inclusion in the global energy calculations. Estimates can vary widely for a given country. This is strikingly evidenced by the 245 TWh and 340 TWh estimated by two studies for U.S. service sector lighting

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[1] Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, USA.

electricity use (Vorsatz et al. 1997 and EIA 1996, respectively).[2] Notably, the large difference between these two studies is more one of methodology than of data. Even greater percentage differences have been noted for IEA countries in the residential sector (Palmer et al. 1998).

The data quality varies over a wide range. Some national estimates are developed based on a simple "residual" analysis, i.e. allocating unidentified parts of the electricity balance to lighting, while others are based on extensive measurement and statistically validated surveys or bottom-up modeling efforts. This points up the need for more rigor and transparency in national lighting energy analysis.

Based on the raw data, we tabulated a variety of "lighting indicators" such as lighting electricity use as a fraction of total electricity, lighting energy per capita and per GDP. We also calculated lighting-related carbon-dioxide (CO_2) emissions based on country-specific emissions factors.

Using the country estimates, we developed least-squares regression models for calculating lighting energy use in each sector for other countries, based on population and GDP corrected for purchasing power parities (Figures 2a-e).[3] Using this method, we constructed a global country-by-country estimate for electric lighting energy use in the year 1997. This estimate represents the 178 countries for which we have sufficient data for performing the analysis.

Two conservatisms in our analysis should be noted:

- The estimates exclude the net effects of lighting on air-conditioning and space heating energy. A very approximate rule of thumb is that one unit of air conditioning energy is saved for every three units of lighting energy saved. Increases in space heating depend highly on the fuel choice and equipment efficiencies. The net effect represents an underestimate of global lighting-related energy use.

- Estimating electricity generation for electric lighting necessitates making an assumption of transmission and distribution losses, for which we stipulate 10%. This significantly underestimates the value for developing countries, where generation, transmission, and distribution losses tend to be substantially higher.

1.2 FINDINGS: ELECTRIC LIGHTING ENERGY & GREENHOUSE-GAS EMISSIONS

The main findings are as follows:

1.2.1 Global Lighting Electricity

- Global electricity lighting electricity production in 1997 totals 2016 TWh, of which 1066 TWh is attributable to IEA member countries.

- The total lighting energy use equates to the output of approximately 1000 large electric power plants, of which 500 are in IEA member countries.[4]

- For the industrialized countries with available data, national lighting electricity use ranges from 5% (Belgium, Luxembourg) to 15% (Denmark, Japan, and the Netherlands) of total electricity use, while in developing countries the value ranges as high as 86% (Tanzania). (Figure 3).

- Total lighting-related carbon dioxide (CO_2) totals approximately 1775 million tonnes (MT), of which approximately 511 MT (29%) is attributable to the IEA member countries.

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[2] We have used the lower of these two estimates in our analysis.

[3] Forced zero-intercepts resulted in somewhat lower correlation coefficients for the individual sectors, but demonstrated better ability to predict lighting energy use when validated against "measured" estimates provided by country sources -- especially in the case of developing countries--and agreed almost exactly with regressions of total lighting energy use with unsuppressed zero-intercept.

[4] Assumes an average plant size of 400 megawatts, a 60% capacity factor, and 10% transmission and distribution losses.

- Few of the studies we compiled distinguish between urban and rural lighting electricity, although significant differences can be expected, especially in the developing world. For example, urban Thailand households use approximately 380 kWh/year of lighting electricity, versus 110 kWh/year for rural homes (Thai Load Forecast Subcommittee 1998). A similar ratio can be seen in Ghana, with approximately 1,300 kWh/year for urban households versus 585 kWh/year for rural ones (Constantine et al. 1999).

1.2.2 IEA Service Sector Lighting Electricity

- Approximately 50% of IEA lighting energy (531 TWh) is used within the IEA service sector.

- Service sector lighting electricity ranges from 3% (Belgium, Italy, Luxembourg, and Portugal) to 10% (Hungary) of total electricity use for the IEA countries evaluated (with an average of 6%).

- Service sector lighting electricity ranges from 39% (Germany and Japan) to 61% (Netherlands) of total service sector electricity use for the IEA member countries evaluated.

- Among the countries for which data are available, we find a range of service sector buildings lighting energy use of 100 to 150 kWh/capita (Greece, Italy, Portugal, Spain) to 1000 to 1300 kWh/capita (Canada, Finland, USA), and from ~10 kWh/$1000 GDP (Belgium, Portugal, Spain, Italy) to ~60 kWh/$1000 GDP (Denmark, France).

- There is a weak correlation between national wealth (measured as GDP/capita) and service sector lighting energy intensities (Figure 2b).

- Total IEA service sector greenhouse-gas emissions are about 261 MT CO_2.

2 FUEL-BASED LIGHTING IN DEVELOPING COUNTRIES

2.1 TWO BILLION PEOPLE WITHOUT ELECTRICITY

Thomas Edison's seemingly forward-looking statement that "we will make electricity so cheap that only the rich will burn candles" was true enough for the industrialized world, [5]but it did not anticipate the plight of 2 billion people—more than the world's population in Edison's time—who 100 years later still have no access to electricity. According to the World Bank, 24% of the urban population and 67% of the rural population in developing countries are without electricity today (World Bank 1996) (Figures 4 & 5).

Unlike heating or cooking, lighting is one of the energy end uses often associated exclusively with electricity. But the reality is different: in fact, about a third of the world's population depends on fuel-based lighting.

The exact number of people who lack direct access to electric lighting is unknown. Barozzi and Guidi (1993) put the value at 2.2 billion, Efforsat and Farcot (1994) at 2.13 billion, and World Bank at just under 2 billion (World Bank 1996). These numbers are underestimates—perhaps considerably so—in that many homes and businesses have only intermittent access to power as in the case of Malaysian villagers surveyed who face forced outages of 6 to 8 hours each day (Manshard and Morgan 1988).

In some instances, the rate of electrification is high and one could argue that fuel-based lighting energy use is a temporary problem. Yet, in Sub-Saharan Africa the rate of per-capita electrification has been only 25% of the birth rate over the past 20 years (i.e. 55 out of 220 million people) (van der Plas 1997). An estimate for Kenya projected rural growth of 65000 to 85000 households in 1996, of which only 4000 to 8000 would have electric grid connections (van der Plas and Floor 1995). In Southeast Asia the net effect of new electrification and population growth was an increase of 250 million people without electricity during the two-decade period of 1970 to 1990 (World Bank 1996). The number of Indian homes using kerosene lighting is said to be increasing by 1 million per

[5] This discussion builds on an earlier analysis by Mills (1999).

year, while kerosene consumption grows by 7.8% annually (Reddy 1997). However, in China, the opposite effect was seen (electrification exceeding population growth). The tug-of-war between population growth and electrification may be resulting in an increase in the number of people without electric light. This was not the lighting future imagined by Edison.

Within the developing world, the extent of rural electrification varies widely from country to country, e.g. about 90% of the population in Africa is not served by grid electricity, versus 20% in Mexico (Figure 6). Some countries (e.g. Burundi, Rwanda, Tanzania) have barely passed the 1% electrification threshold. In Ghana, even 6% of urban households used fuel-based lighting (Haggan and Addo 1994). While the levels of illumination provided by flame-based lamps are far lower than with modern electric lighting, the efficiency of fuel-based light production is also low. The result is a substantial amount of primary energy use with little service received in return.

For individual households, the cost of kerosene is a burden and is far more expensive than electric lighting. The cost per useful lighting energy services ($/lumen-hour of light) for kerosene lighting is 325-times higher than that for "inefficient" incandescent lighting and 1625-times higher than for compact-fluorescent lighting (Table 2). To put these numbers in perspective, the total <u>annual</u> light consumption (about 12000 lumen-hours) in a typical un-electrified household is equivalent to that produced by a 100-watt incandescent bulb in 10 hours. While households lit with flame-based lighting spend approximate the same amount of money each year on lighting (approximately $100/year), they receive far less than one percent as much lighting services as their counterparts in electrically-lit homes in IEA countries.

2.2 RELIANCE ON FUEL-BASED LIGHTING

There are a wide variety of fuel-based light sources, including candles, oil lamps, ordinary kerosene lamps, pressurized kerosene lamps, biogas lamps, and propane lamps. According to most studies, ordinary wick-based kerosene lamps are the most common type of fuel-based lighting in developing countries. One estimate puts the estimate for India at over 100 million (Louineau et al 1994; Reddy 1981). Ironically, more efficient kerosene lamps tend to increase both light output and fuel consumption, whereas an efficient electric compact fluorescent lamp provides an eight-fold reduction in primary energy consumption compared to standard incandescent light sources (Dutt and Mills 1994).

According to a study by van der Plas and Floor (1995), typical household kerosene lamp use is 3 to 4 hours per day, with weekly fuel consumption of about 1 liter. Typical light outputs are 10 to 15 lumens for locally made lamps and 40 to 50 lumens for store-bought models.

A study conducted by the joint UNDP/World Bank Energy Sector management Assistance Programme (ESMAP) found rural households spending as much as US$10 per month on lighting from candles, kerosene and dry-cell batteries. This operating cost is similar to that paid by industrialized households with two-dozen bright light sources throughout their home (e.g. ~100 kWh at $0.10/kWh). A survey of 351 Malaysian households identified monthly household kerosene expenditures for lighting at approximately $20 (Manshard and Morgan 1988), and half of these homes were electrified.

Many suppliers of energy-efficient lighting equipment have not found the rural markets in developing countries worth exploring. However, the large amounts of money spent on lighting fuel indicates that there is a considerable potential for spending money on alternatives, for instance photovoltaic-based lighting solutions. This was verified in a field test by the World Bank (van der Plas 1998).

2.3 GLOBAL ENERGY DEMAND FOR FUEL-BASED LIGHTING

We have found no prior estimate of the global lighting energy use associated with fuel-based lighting. One is developed here, attempting to capture the uncertainties by considering a range of values for important factors that are not well known. We assume an non-electrified population of 2 billion and take the locally made kerosene lamp as the reference light source, the rate of fuel consumption at 0.04 to 0.06 litres per hour, and daily usage of 1.5 to 4.0 lamp-hours per capita.

An additional uncertainty is the number of people per household. We found only one such estimate, which, fortunately, represented a very significant portion of the total unelectrified households in the world -- India. According to Bandyopadhyay (1995), of the average village population is 1128 people (580,000 villages in total) with an average family size of 5.6 people per household.

The corresponding range of assumptions is consistent with limited field data (Mills 2000).[6] Our interviews in Cambodia (where about 90% of the homes are un-electrified) found 3 lamps per household, with a fuel use rate of 0.05 liter per hour. In some cases, one kerosene lamp is used throughout the night for safety (security) purposes. In Bhutan those we interviewed reported the use of 2 to 4 kerosene lamps per household, and 5 to 20 liters/month kerosene use. With 85% of Bhutan's population living more than an hour's walk from the nearest road, electrification rates are low there as well.

We have estimated only the non-electrified household sector's contribution to fuel-based lighting, lacking sufficient basis for assumptions necessary to evaluate the service and industrial sectors (Mills 2000). Pressurized kerosene lamps used in businesses have a much higher hourly rate of fuel-use. The energy requirements for the many households who use fuel-based lighting as an alternate light source (e.g. during blackouts) have also not been estimated.

2.4 FINDINGS: FUEL-BASED LIGHTING

The main findings, including ranges from Table 3, and contrasted with global electric lighting totals in Table 4, are:

- Household fuel-based lighting is responsible for annual energy consumption of 96 billion litres of kerosene (or 3603 petajoules, PJ). For comparison, the <u>total</u> energy use (all sectors and fuels) in Austria is 1200 PJ, in Sweden 2200 PJ, and in the UK 10000 PJ). This also equates to 1.7 million barrels of oil today, comparable to the total production of Algeria, Brazil, Indonesia, or Libya, and about 65% that of Iraq.

- The primary energy consumed for this fuel-based residential lighting is 64% of that used to provide the 487 TWh of electricity consumed for household electric lighting globally, and 115% of that to make electric lighting for households within IEA countries.

- The cost of this energy is $48 billion/year (assuming a kerosene price of $0.50/ liter), or approximately $100 per household. This corresponds to 98% of the costs from residential electric lighting globally, and 161% of electric lighting for households within IEA countries.

- Fuel-based lighting results in 244 million metric tonnes of carbon dioxide emissions to the atmosphere each year, or 58% of the CO_2 emissions from residential electric lighting globally, and 156% of that to make electric lighting for households within IEA countries.

- Within the developing countries, national fuel-based lighting energy use can be on a par with that for electric lighting, and is large even compared to total electricity used for all purposes. One study noted that kerosene accounted for nearly 60% of the total energy requirement for lighting in India's household sector in 1986. This is generally consistent with our own findings. According to our "central" estimates, fuel-based lighting in Brazil consumes 40% as much energy as that required to produce the electricity used for lighting in the country.

2.5 THE IMPERATIVE OF IMPROVED LIGHTING SERVICES IN THE DEVELOPING WORLD

The state of affairs concerning fuel-based lighting is worrisome. Oil import dependency is generally high in developing countries, and it drains valuable hard currency. By virtue of its inefficiency, fuel-based light is hard to work or read by, imposes a high cost on very poor households (and strains the budgets of governments who subsidize fuel prices), and seriously compromises indoor air quality. Women are typically saddled with the burden

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[6] Some other studies suggest lower rates of fuel use (Hagan and Addo 1994; Craine 2002). In one case, this is due at least in part to the population of homes surveyed being partially electrified.

of obtaining kerosene, which often involves walking long distances (Haggan and Addo 1994). Meanwhile, electrification (for the sake of lighting and other energy services) has its own problems, not the least of which is the extraordinary cost of electricity transmission and distribution costs coupled with the high capital costs and low system efficiencies associated with providing centralized power generation in such conditions.

Further complicating matters, kerosene costs are typically subsidized, by 50% in the case of India (Manzoor et al 1998). One of the adverse side effects of such subsidy systems is that once kerosene becomes less expensive than gasoline truck drivers will use it to dilute diesel fuel (thus exacerbating air pollution and scarcity problems) (Dutt n/d; Reddy n/d). Another complication is that subsidized prices are particularly prone to price spikes as pricing policies shift. Kerosene pricing and subsidies are often the source of political and social unrest, hoarding, and scarcity (Business Week 2000; Katmandu Post 2000; NepalNews.com 2000).

Among the more startling implications of our findings is that users of fuel-based lighting in the developing world spend a comparable amount of money household lighting as do households in the industrialized world, but receive a vastly smaller level of services (Figure 7). On a percentage-of-income basis, households in developing countries spend hundreds of times more for lighting services than their counterparts in the North.

Some argue that the problem of fuel-based lighting is not a priority given the environmental impacts and costs of other end uses, such as cooking. While that zero-sum analytical perspective is certainly debatable, few would dispute that improving the quality and quantity of light available to households in the developing world would yield dramatic social, health and other important non-energy benefits.

Perhaps the most intriguing effort thus far to address the issue is an initiative from the University of Calgary to deploy white LED-based lighting systems in developing countries. Early efforts have met with significant success, including many demonstration homes in Nepal (Irvine-Halliday *et al.* 2000). Base-case lighting sources ranged from resin-coated sticks, to candles, to kerosene lamps. The team developed 2- to 9-LED circular luminaries (less than one watt total power) for a variety of uses in Nepalese homes, deploying the systems in 143 homes in 6 villages. Their preferred power supply is a low-scale hand- or pedal-powered generator, which requires 30 minutes of slow operation per day to charge a batter sufficiently to run LED lights in one home. The proponents of this approach note the added advantages of rugged, ultra-long life for the LEDs, and the ability to manufacture, maintain, and repair the luminaries and pedal-power generators within developing countries. LED luminaries also operate 200-times longer on D-cell batteries than the typical incandescent "torches" (flashlights) used by many villagers, resulting in a dramatic reduction in the volume of discarded batteries. As a testimonial for the improved efficacy of LED sources, one Nepalese village providing light to three homes from a 200W Pico Hydro generator, was able to subsequently power 28 homes after switching to LEDs. Another 200W pico-hydro system in Nepal costed out at $132/household (over 53 households) versus a nearby micro-hydro project (8000W) to power incandescent lighting in 70 houses at a 5.5-fold higher cost of $714/household (Craine and Lawrance 2002). The pico-hydro system cost is on a par with what a typical household pays in a year for kerosene lighting fuel.

3 GLOBAL LIGHTING ENERGY SAVINGS POTENTIAL

3.1 LIMITATIONS OF PAST WORK

We identified 13 studies estimating national or regional lighting savings potential (Table 5). Among these, most focused either on a specific technology (e.g. compact fluorescent lamps) and/or on a specific policy option (e.g. ballast standards). The studies also differ in whether they provide a technical potential (with no moderating assumptions for partial penetration or cost-effectiveness) versus a potential bounded by application-specific, market, or economic constraints.

Only three studies—covering Sweden and the United States—employed a detailed "supply-curve" style analysis for costing and ranking technology options and (Atkinson et al. 1992, Swisher et al. 1994, and Vorsatz et al 1997). An study of ballast standards for the European Union employed a simple payback analysis (Webber and Slater ND).

Only one study dealt in any quantitative detail with the question of the net effects of lighting on heating and cooling energy (Sezgen et al 1994), although Nutek (1995) also made an attempt to account for this. We found only three studies (Atkinson et al. 1992; Granda 1997; Palmer et al. 1998) that computed lighting-related greenhouse-gas emissions and savings.

Most studies are unclear as to the reference case from which their “efficient” scenarios are developed. One study was very explicit in this for the U.S. (Atkinson et al. 1992) and three did so for Sweden (Bodlund et al. 1989; Swisher et al. 1994; Nutek 1995). Most studies are poorly documented.

Based on Table 5 and our review of the literature, we determined a savings potential of 8800 to 12300 Petajoules for electricity and kerosene (Table 6). Note that these rough estimates are “overnight” savings, i.e., based on today’s consumption levels. Re-computed for a future date based on a growing ‘business-as-usual’ reference case, the absolute value of the savings would of course be greater. Kerosene use for lighting is growing particularly quickly.

3.1.1 Electricity Savings

Our electricity savings estimates represent a hypothetical policy pathway that includes a combination of modest standards and aggressive voluntary programs promoting cost-effective lighting efficiency improvements using today’s technologies. In practice savings will vary by country, depending on existing baseline conditions, etc.

Several conservatisms should be noted. Illuminance-level recommendations vary widely among IEA countries (Mills and Borg 1999). While rarely addressed by lighting energy policy analysts, these variations have significant energy implications, potentially leading to reduced lighting energy demand if standardized at a moderate level. Daylighting savings are not included here due to a lack of data on which to base national savings potentials. Note that these savings estimates also do not include the net indirect effects on space heating and air-conditioning in buildings. As an illustration of the greater potential that may be achieved by considering the above-mentioned factors, Nutek (1995) developed a 64% high-efficiency lighting savings potential for the service sector.

Another way to consider the savings potential is to compare lighting energy intensities across countries. As seen in Figure 2, for a given level of gross national product, we can readily observe a factor of two (or more) variability in per-capita lighting energy intensities among wealthier countries. Note that while it may be tempting to ascribe these differences to differences in daylight availability in southern versus northern regions, this correlation is not visible in the data.

The electricity savings shown in Table 6 correspond to approximately 550 to 890 TWh, or the electrical output of 240 to 385 400-megawatt power plants.

3.1.2 Fuel-Based Lighting Savings

Developing a savings potential for fuel-based lighting is conceptually more difficult than in the case of electric lighting, given the extremely low service levels today and a wider spectrum of potential technology choices. Per-lamp illuminance is typically 100-times lower than that for modern electric lamps. For fuel-based lighting, savings are generally high when assuming substitution of electricity and no increase in energy services (light levels).

To identify the envelope of possibilities, we developed nine scenarios for fuel-based lighting, based on three types of electric lighting: incandescent, compact fluorescent, and white LED, and three tiers of numbers of light sources per households (Table 7). Given the extreme inefficiency of kerosene lamps, even the use of incandescent replacements generally results in a reduction in costs and greenhouse-gas emissions and a 100- to 300-fold increase in energy services (lumens produced).

The "thought experiment" of increasing the numbers of light sources to the point that carbon emissions begin to rise shows that two incandescent lamps for each existing kerosene lamp is the limit, versus 8.5 lamps for CFLs, and 128 lamps for LEDs. These three scenarios bear identical operating cost savings of approximately 50%, but yield 200-, 800-, and 12,000-fold increases in service levels, respectively. However, substantially increasing service levels (light production) is not possible with incandescent sources without elevating both carbon emissions and operating costs. For example, increasing from the existing baseline of three lamps per household to ten incandescents would result in a quadrupling of emissions and a 140% increase in operating cost. Similarly, ten CFLs would cause emissions to rise by 17%, although costs could still decline.

A shift to white LEDs, however, gives very substantial cost and emissions savings, even for an increase from three to ten light sources per household. Further emissions reductions could be achieved with LEDs powered by local renewable energy supplies, based on highly successful demonstration projects that have been conducted by Irvine-Halliday (2002). The central conclusion of this exercise is that homes in the developing world could be lit to the same standards as those in industrialized countries, while reducing the cost burden and emissions released to the environment. At least in the case of lighting, attaining a higher standard of living does not require increased use of energy.

4 CONCLUSIONS AND RECOMMENDATIONS

Global lighting energy use is significant, totaling approximately $230 billion per year. The potential for reducing lighting energy use, associated costs, and emissions is clearly substantial. The lower end of the electricity savings range presented here is greater than the total individual national electricity use of Canada, France, or Germany. Savings in kerosene lighting exceed the oil production of Algeria, Brazil, Indonesia, or Libya. The single-greatest way to reduce the greenhouse-gas emissions associated with lighting energy use is to replace kerosene lamps with white LED lighting systems in developing countries. Further work is clearly needed, however, to improve both the baseline energy use data and the appropriate savings factors.

Given the potential for lighting energy savings, it is remarkable how little effort has been expended by most nations to quantify the electricity used for lighting. While the collection of end-use energy data is arguably not a high national priority in most countries, this lack of attention is particularly problematic in this instance given that lighting is usually an early and preferred target for energy savings campaigns and policies.

It is equally remarkable how little data have been collected on the lighting markets themselves (e.g. shares, performance, and utilization, of specific types of lighting components in the stock and in new sales). Without such data, precise scenarios of future lighting electricity demand cannot be developed.

The world's 2 billion users of fuel-based lighting collectively consume significant amounts of energy and emit correspondingly large amounts of greenhouse gases, even compared to households served with luxurious electric lighting. However, fuel-based lighting has been largely ignored in global energy analyses. Our investigation shows its importance in the domestic sector, indicating energy use on a par with electric-based lighting energy in the home. Thanks to low lamp efficiencies, fuel-based lighting expenditures rival those seen by affluent households who enjoy the vastly higher levels of quality, safety, and services provided by electric light. Analyses have yet to be conducted of fuel-based lighting in the non-residential sector, where demand is also expected to be substantial. Moreover, substitution of standard inefficient electricity electric light sources for fuel-based lighting could radically increase global electricity consumption for household lighting. Conversely, the single-greatest way to reduce the greenhouse-gas emissions associated with lighting energy use is to replace kerosene lamps with white LED lighting systems in developing countries.

Given the information gaps and quality issues concerning the data we have identified, we view new initiatives to enhance lighting data availability and quality as an enormous opportunity area. A coordinated lighting energy survey would also ensure better consistency and inter-comparability of country-specific estimates.

5 FURTHER RESEARCH NEEDS

Once consistent and more thorough lighting estimates are gathered, it would be possible to make more substantive savings projections, and to better test the impact of a variety of policy measures alone or in combination.

Among the important data collection and analyses going forward are:

- **New and improved country-specific electric lighting data –** In many cases multiple estimates are available for a given country, sometimes varying widely. Existing data should be better evaluated, while data for additional countries compiled and integrated with our global estimation formula. More recent lighting estimates should also be collected, and used to update the predictive model. This is especially important for areas where electrification rates are changing. Improved and consistent methodologies for estimating national lighting energy use would also improve our understanding of electric lighting energy demand. Among the best in-country examples we identified is the survey conducted by the Energy Information Administration of the U.S. Department of Energy (EIA 1996b). Improved studies would ideally collect more than lighting energy data, extending the compilation to include lighting market statistics (e.g. as done by EPRI 1992; Sezgen et al 1994; Nutek 1995; Vorsatz et al. 1997; or EIA 1998).

- **Further investigations of fuel-based lighting –** This is clearly an under-appreciated opportunity area. Improved data on fuel costs, lamp efficiencies, and utilization of fuel-based lighting are all critical to helping identify and tap a potential $25- to 36-billion annual savings opportunity.

- **Improved industrial lighting data –** Information is particularly scarce in the area of industrial lighting energy issues. Our data collection showed that industrial lighting represents about 20% of the IEA lighting total nearly (2/3 the size of residential). Yet, we encountered no national-scale studies that evaluated the energy savings potential for this important sector, and the available baseline analysis is usually less thorough than that for the residential and commercial sectors.

- **Further data analysis –** improved indicators of lighting energy intensities would be of value in comparing lighting energy use across countries. Incorporation of country-specific energy prices and carbon emissions factors would refine the results presented here.

- **More sophisticated prediction tools –** We have built up our global lighting energy estimates using a basic regression model of population and GDP as determinants of lighting energy use. Additional end-use indicators should be sought, along with establishing a basis for projecting growth in lighting energy use.

- **Influence of electricity prices on lighting energy use –** A simple correlation study of country-specific prices and lighting energy demand would illustrate the importance of the price factor in context with the technical and cost-effective savings potential.

- **Improved estimates of lighting electricity generation –** electricity transmission and distribution losses vary widely, especially within developing countries. We have used a conservative global-average estimate of 10%, which could be replaced by country-specific values where available.

- **Fuel-based lighting in the non-residential sector –** Fuel-based lighting energy use in the service and industrial sectors is probably on a par with that identified for households in this study, but further data collection is required before it can be quantified.

- **Energy savings potentials –** Our preliminary savings estimate for the service sector should be expanded to cover all other sectors, including fuel-based lighting.

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Table 1. Compilation of lighting energy use estimates, by country.

	Estimates of Lighting Electricity Use by Country						Lighting End-Use Shares						
Country	Total light (TWh)	Residential (TWh)	Services (TWh)	Industrial (TWh)	Street (TWh)	Other (TWh)	Lighting as Fraction of Total Elect.	Lighting as Fraction of Total Resid'l	Lighting as Fraction of Total Services	Lighting as Fraction of Total Industrial	Data Year	Sources	Comments
Australia*	14.21	2.78	8.30	2.33	0.80		9%		33%	4%	1993	Com'l: Australia Department of Energy (1996); Street Light (Australia DoE, 1998); Ind'l from Warren Julian (University of Sydney); Residential: Bates (1999)	Data for New South Whales region, scaled to national totals by ratios of total TWh for NSW vs Australia
Austria*	4.17	1.07	2.20	0.90			8%					EC (ND), p. 13	Palmer value used for Resid'l, vs 1.00 from EC (ND), p. 13
		1.07									1995	Palmer et al (1998), p. 18	
Belgium*	4.06	1.16	2.10	0.80			5%					EC (ND), p. 13	Palmer value used for Resid'l, vs 0.90 from EC (ND), p. 13
		1.16									1994	Palmer et al (1998), p. 18	
Brazil	47.07	11.08	23.80	2.50	9.69		17%	25%	44%	2%	1996	Leonelli (Right Light 111), p. 177; Jannuzzi, Dos Santos, Bittencourt, and Leonelli (RL IV), p. 7; Jannuzzi and Dos Santos (RLIII)< p. 171	Authors' % applied to IEA totals
		4.56	7.59									WEC 1995	
Bulgaria	3.70	1.04	1.11	0.93	0.4	0.2	10%				1996	Vassilev, 1997 (p. 299); Vaneva and Welinov (1997)	
		1.05									1992	Palmer et al (1998), p. 18	
Canada*		16.49	38.39		2.30			12%	33%		1996	Natural Resources Canada 1998	
China	122.00	45.44					12%				1996	T: Fu Min, et al, RLIII; R: WEC 1995	
	100-130										1995	Hong and Dadi, 1997 (p. 191)	
Denmark*	5.28	1.30	2.88	1.10			15%				1996	EC (ND), p. 13	
		1.40										Palmer et al (1998), p. 18	
		1.50									1995	Ulander - IEA/LBL Database (1995)	
Finland*	9.99	2.02	5.77	2.20			14%					EC (ND), p. 13	Palmer value used for Resid'l, vs 1.35 from EC (ND), p. 13
		2.02									1995	Palmer et al (1998), p. 18	
		1.80									1994	Ulander - IEA/LBL Database (1995)	
France*	32.20	11.40	15.00	5.80			8%					EC (ND), p. 13	Palmer value used for Resid'l, vs 6.8 from EC (ND), p. 13
		11.40									1994	Palmer et al (1998), p. 18	
Former Soviet Union	220.00					16.9	20%				1990	Aizenberg (1993), p. 187.	For "FSU" baseline data, IEA data for the following countries were combined: Russia, Ukraine, Georgia, Kazakhstan, Kyrgystan, Tajikistan, Uzbekistan, Estonia, and Latvia. Lithuania is evaluated separately in this table.
Germany*	67.57	28.37	26.54	12.66			13%					EC (ND), p. 13	Palmer value used for Resid'l, vs 11.14 from EC (ND), p. 13
		9.50									1995	Ulander - IEA/LBL Database (1995)	
		28.37									1997	Palmer et al (1998), p. 18	
Ghana		1.02						63%			1996	Constantine, S. et al. (1999). Pp. 42.	
Greece*	3.64	1.24	1.70	0.70			9%					EC (ND), p. 13	Palmer value used for Resid'l, vs 0.80 from EC (ND), p. 13
		1.24									1988	Palmer et al (1998), p. 18	
Hungary*	5.54	2.03			0.6		17%	21%			1998	Personal Communication, Diana Vorsatz, CEU, 9/30/99	
India	55.23	13.18	29.13	12.92	2.0		15%	28%	60%	9%	1996	Total lighting share applied to 1996 TWh, and residential total from Kirpal. Lighting shares within sectors, and industrial TWh estimate, from Dua and Sabharwal p. 582. S: Dutt (n/d), p. 19.	
		44.54	4.45									R: WEC 1995	
	29.00											T: Dutt (n/d, p.5	
Ireland*	1.67	0.57	0.80	0.30			10%						Palmer value used for Resid'l, vs 0.40 from EC (ND), p. 13
		0.57									1996	Palmer et al (1998), p. 18	
Israel	5.59	0.95	2.31	2.33			19%	10%	50%	30%	1992	Souzi (1993), p. 439-440	Fractions from Souzi applied to IEA energy values for 1996
Italy*	18.82	7.22	8.40	3.20			7%					EC (ND), p. 13	Palmer value used for Resid'l, vs 6.8 from EC (ND), p. 13
		12.70									1995	Ulander - IEA/LBL Database (1995)	
		7.22									1995	Palmer et al (1998), p. 18	
Japan*	146.29	45.35	57.05	43.89			15%	17%	33%	8%	1996	Noguchi et al (199_), p.364. Percentage applied to 1996 total TWh	Lighting shares applied to IEA totals
		28.40	199.50								1995	R: Ulander - IEA/LBL Database (1995); C: WEC 1995	
		24.50										R: WEC 1995	
Lithuania	1.48	0.31									1995	Kazakevicius et al 1997), p. 287	
Luxembourg*	0.29	0.07	0.16	0.06			5%					Palmer et al (1998), p. 18	
Mongolia	0.24	0.08	0.09	0.07	0.005		14%	30%	26%	6%	1996	Lubsan (1993), p. 183.	
Mexico		3.48										R: WEC 1995	
Netherlands*	14.24	2.97	8.75	2.52			15%					EC (ND), p. 13	
		3.38									1996	Palmer et al (1998), p. 18	
New Zealand*	3.05	0.90	1.35	0.80								Vickers (1999)	
Norway*	14.00	3.20					13%	25%	60%		1995	Total: Brekke and Hansen (1993), p. 876; Res'l Ulander - IEA/LBL Database	
Pakistan									70%			De Almeida. 1998., p. 572	
Poland	14.64	7.74					12%				1996	Percentage from 1993 applied to 1996 total TWh. Skoczek (1993), p. 752.; Residential from Palmer et al (1998), p. 18.	
		6.57									1995	Grzonkowski et al 1995.	
		14.55						55%				Granda, 1997 (p. 271)	
Portugal*	2.00	0.50	1.10	0.40			6%					EC (ND), p. 13	
		1.36									1995	Julio et al 1995	
Romania					0.27						1994	Burlacu (1995)	
South Africa				10.57				13%		5%		Henderson, RL IV, p. 199	Applied author's lighting percentage share to IEA elect total
Spain*	14.00	6.00	5.80	2.20			9%						
		6.00									1995	Palmer et al (1998), p. 18	Palmer value used for Resid'l, vs 2.6 from primary source
Sweden*	12.94	3.22	6.03	2.50	1.2		10%				1991	Nutek 1995	
	13.10	2.50	6.40	3.00	1.2						1989	Swisher, 1994, p. 582.	
		2.80									1995	Ulander - IEA/LBL Database (1995)	
		3.12									1997	Palmer et al (1998), p. 46	
Switzerland*	5.56	1.39	3.33	0.83			12%	9%	26%	5%	1990	Personal Communication, Bernard Aebischer, ETH Zurich	Estimates for 1990 scaled for 17% 1990-1996 growth in total Swiss Elect.
Taiwan		1.43	1.63									R: WEC 1995; C: WEC 1995	
Tanzania	1.54	0.42			0.008		86%	84%	90%		1993	Gullbert et al 1999; using lighting shares for Urambc	
Thailand		1.70						9%			1998	Thai Electricity Load Forecast (1998)	Incandescent fraction for Provincial Energy Authority estimated per that reported for Metropolitan Energy Authority
Turkey*													
United Kingdom*	47.80	17.50	21.70	5.90		2.7	14%					EC (ND), p. 13, plus Heywood and Rowbury for "other"	Palmer value used for Resid'l, vs 8.8 from EC (ND), p. 13
	40.00	7.80	23.50	6.00		2.7						Heywood and Rowbury, RL III	
		17.50									1996	Palmer et al (1998), p. 45	
USA*	450.03	135.00	245.70	54.33	15.0		13%	12%	32%	7%	Various	Vorsatz et al, 1997 p. 6 (resid'l), p. 25 (com'l), Atkinson et al 1992, Streetlighting. Industrial (1994) from USDOE/EIA-0512 (94), p. 89	Lighting share of services calculated using CBECS 1995 total electricity value of 764 TWh.
		110.60									1995	Ulander - IEA/LBL Database (1995)	
		94.00	340.00					9%	36%		1995	US EIA (reported in Vorsatz et al 1997)	
** IEA Member Country*		114.15	379.67									R: WEC 1995; C: WEC 1995	

Table 2 Equity considerations of fuel-based lighting: comparative performance of kerosene and electric lighting.

	Compact Fluorescent Lamp	Simple Kerosene Lamp	Units	Comment
Assumptions				
Energy price	10 c/kWh	$0.50/liter		
Energy consumption	15 Watts	).05 liters/hr		
Energy services provided	975	10	lumens	
Ratio	**98**		**:1**	**CFL provides nearly 100-times more light output**
Primary Energy Consumption				
Electricity	10.47		MJ per kilowatt-hour	
Kerosene		37.6	MJ per liter of kerosene	
Energy per equal service (975 lmn-hrs)	0.015	4.875	kWh or liters	
MJ per service (975 lumen-hours)	0.15705	183.3	MJ	
Ratio		**1167**	**:1**	**Kerosene lamp requires 1167-times more energy to deliver a unit of services (lumens)**
Cost per unit of energy services				
Operating time for equal service	1	98	hours	Operating time to generate a set amount of light output (975 lumens, in this case)
Services	975	975	lumen hours	
Cost for equal service	$0.00	$2.44	$/lumen-hour	Cost for providing set amount of light output
Ratio		**1,625**	**:1**	**Kerosene lamp costs 1625-times more than CFL to deliver the same level of energy serice (975 lumen hours)**

Note: This range reflects the spectrum of the lesser-efficient kerosene lamps to the more-efficient electric light sources.

Table 3. Energy Used for Household Fuel-Based Lighting in Developing Countries.

	High	**Central Estimate**	Low
Household Lighting Characteristics			
Population without electricity	2,000,000,000	**2,000,000,000**	2,000,000,000
People per un-electrified household	4	**4**	4
Unelectrified households	500,000,000	**500,000,000**	500,000,000
Kerosene lamps per household	4	**3**	2
Number of lamps	2,000,000,000	**1,500,000,000**	1,000,000,000
Lamps per capita	1.00	**0.75**	0.50
Fuel consumption per lamp (liters per hour)	0.06	**0.05**	0.04
Daily lamp use (hours)	4	**3.5**	3
Lamp-hours per capita per day	4.0	2.6	1.5
Annual Energy Use			
(liters kerosene)	175,200,000,000	**95,812,500,000**	43,800,000,000
(GJ)	6,587,520,000	**3,602,550,000**	1,646,880,000
(PJ)	6,588	**3,603**	1,647
(MTOE)	155	**85**	39
(Millions of barrels of oil per day)	3.1	**1.7**	0.8
Energy Use Comparison			
Primary energy to make global fuel-based lighting (PJ)	6,588	**3,603**	1,647
Primary energy to make global res'l lighting electricity (PJ)	5,604	**5,604**	5,604
(of which IEA)	3,122	**3,122**	3,122
Total primary energy (fuel + electric lighting)	12,191	**9,206**	7,251
Fuel-based lighting / Electric Lighting	118%	**64%**	29%
Fuel-based lighting fraction of total	54%	**39%**	23%
(fuel-based energy vs IEA electric)	211%	**115%**	53%
Cost Comparision			
Cost of Fuel-based lighting ($B)	88	**48**	22
Cost of global household electric lighting ($B)	49	**49**	49
(of which IEA)	30	**30**	30
Total cost (fuel + electric lighting)	136	**97**	71
Fuel-based lighting / Electric Lighting	180%	**98%**	45%
Fuel-based lighting fraction of total	64%	**50%**	31%
(fuel-based cost vs IEA cost)	294%	**161%**	73%
Emissions Comparison			
CO2 emissions from fuel-based lighting (MT CO2)	447	**244**	112
CO2 emissions from global residential electric lighting (MT CO2)	420	**420**	420
(of which IEA)	157	**157**	157
Total emissions (fuel + electric lighting)	866	**664**	531
Fuel-based lighting / Electric Lighting	106%	**58%**	27%
Fuel-based lighting fraction of total	52%	**37%**	21%
(fuel-based fraction vs IEA)	285%	**156%**	71%
Energy Services Comparison			
Fuel-based lighting users (Trillion lumen-hours)	29	**19**	11
Electric-lighting users (Trillion lumen hours)	12,164	**12,164**	12,164
Ratio	417	**635**	1,111
Fuel-based lighting (lumen-hours/capita)	14,600	**9,581**	5,475
Electric-lit homes (lumen-hours/capita)	3,041,096	**3,041,096**	3,041,096
Ratio	208	**317**	555
Per Household Comparisons: Services & Costs			
Energy Services Provided (1000 lumen-hours per household)			
Fuel-based lighting	58	**38**	22
Electric Lighting (60-watt lamps instead of kerosene)	5,694	**3,737**	2,135
Ratio:	98	**98**	98
Cost ($/year-household)			
Electrified (IEA countries, assume 2.5 people/hh)		**82**	
Fuel-based	175	**96**	44
Electricity use if per-capita use = IEA electric average (TWh)		**723**	
percentage of global household electric lighting energy in 1997		**220%**	

Assumptions and conversion factors : 1 liter kerosene = 37.6 MJ; 1kWhe = 10.47 MJ; 0.068 MTCO2/PJ kerosene;
kerosene lamp produces 10 lumens of light; 60W incandescent lamp generates 900 lumens
0.0955 TWhe/PJ. Does not include electrified households that use supplemental fuel-based lighting.
Electricity cost $0.10/kWh; kerosene cost $0.50/liter. 1TWhe = 25 trillion lumen-hours,
reflecting a weighted-average efficacy of 25 lumens/watt across all types of light sources in IEA homes.
1 bbl oil = 6.12 GJ; 1MTOE = 7.33 Mbbl. Sources for utilization data: Louineau et al (1994); van der Plas & Floor (1995).

Table 4. Electric versus fuel-based lighting: relative global energy use, emissions, costs, and services delivered.

	Population (billion)		Energy (Petajoules /yr.)		Greenhouse-Gas Emissions (MT CO2/yr.)		Energy Cost ($ billion/yr.)		Energy Services (Trillion lumen-hours/yr.)	
Electricity	4	67%	21103	85%	1775	88%	183	79%	12164	99.8%
Fuel	2	33%	3603	15%	244	12%	48	21%	19	0.2%
Total	**6**		**24706**		**2020**		**231**		**12184**	

Table 6. Global lighting energy savings potential.

	Baseline Energy Use (PJ/year)	Savings Potential	Savings (low)	% of total savings	Savings (high)	% of total savings
Electric Lighting						
Residential	5,604	40-60%	2,242	25%	3,362	27%
Commercial	9,551	25-40%	2,388	27%	3,821	31%
Industrial	3,272	15-25%	491	6%	818	7%
Streetlighting & Other	1,507	25-50%	377	4%	753	6%
Fuel-based Lighting						
Residential	3,603	92-99%	3,300	38%	3,581	29%
Total	**23,536**	**37%-52%**	**8,797**	**100%**	**12,335**	**100%**

Note: Savings range for kerosene represents CFL - LED technology choice.

Table 7. Scenarios of energy and emissions reductions for fuel-based lighting in developing countries.

	Number of Light Sources	Annual GHG Emissions (MT CO2)	Change	Annual Cost ($B)	Change	Service Level (lumens/house)	Service Index (Basecase=1)
Baseline - 3 Kerosene Lamps per Household	**3**	**244**	**--**	**48**	**--**	**30**	**1**
Baseline Number of Light Sources							
60W incandescents	3	115	-53%	11	-77%	2,700	90
15W CFLs	3	29	-88%	3	-94%	2,700	90
1W LEDs	3	2	-99%	0.2	-99.6%	90	3
More Light Sources							
60W incandescents	10	1150	371%	115	140%	9,000	300
15W CFLs	10	287	17%	28.7	-40%	9,000	300
1W LEDs	10	19	-92%	2	-96%	300	10
Constant Carbon Emissions							
60W incandescents	2.1	244	0%	24	-50%	1,890	63
15W CFLs	8.5	244	0%	24	-50%	7,650	255
1W LEDs	128	244	0%	24	-50%	3,840	128

Table 5. Studies of national or regional lighting energy savings potential.

Country or Region	Title	Pub. Date	Published by	Sector(s)	Baseline data	Baseline Scenarios	Efficient Scenarios	Savings Potential	Scope of Scenario	Enduse Detail	Market Data	CO2	Comments
Bulgaria	Possibilities for the Improvement of Energy Efficiency of Electric Lighting in Bulgaria	1997	Technical University, Sofia-lighting Lab	R, C, I, S, O	R, C, I, S, O	None	Overnight			By subsector	Middle	No	
China	Energy efficient lighting in China	1997	Lawrence Berkeley National Laboratory	National	National	Overnight	Overnight	41%-61%	Lamp efficiency improvements, national, by lamp type	By lamp type	Light source producution	No	Lower savings estimate is for bringing light sources up to western performance standards; Higher savings estimate is for substitution to premium efficiency products.
EU	Lighting and Energy in Buildings	1996	BRE									No	
EU	DELight	1998	Univeristy of Exford, Swedish national Energy Administration, Energiestiftung Schleswig-Holstein	R	R	2020	2020	43%	CFL Focus (?)		Extensive, mostly housing stock and consumer attitude surveys	Yes	Detailed estimates for Germany, Sweden, and UK extrapolated to all EU
Europe	Study on the Cost Benefit Analysis of the Impelemntaton of Minxxxx	ND	EC	R, C, I	R, C, I	2020 (C & I)	2020 (C & I)	Resid'l: 12%-20% Com'l: 10%-18% Ind'l: 10%-18%	Fluorescent ballasts only	Extensive for this equ	Extensive	No	Scenarios and market data pertain only to lamp ballasts
Europe	GreenLight	ND	European Commission Joint Research Centre	C	C	Overnight	Overnight	30-50%	Various			No	Based on case studies of GreenLight projects in Belgium, Norway, Italy, and Portugal.
India	Energy Efficient Lighitng in India - Potential and Strategies	1993	Ministry of Power; Energy Management Center	R, C, I	R, C, I	2005	2005	10-90%	By lamp type	By lamp type	by sector and by lamp type	No	
Lithuania	Assessing the Residential Lighting Efficiency…	1997	Lawrence Berkeley National Laboratory	R	R		Overnight	54%	Replace 2 incandescents per home with CFLs				
Poland	Case Study: The IFC/GEF Poland Efficient Lighting Project	1997	IAEEL	R	R	None	Overnight			Middle	Middle	Yes	Scenarios focus strictly on a CFL program
Sweden	Framtida Elvaendning--Effektiviseringspotentialer	1995	Swedish National Board for Industrial and Technical Development	R,C,I, S	R,C,I,S	2020	2020	Resid'l: 29%; Com'l: 64%; Ind'l: 69%; Streetlight: -55%	Comprehensive			No	
Sweden	Dynamics of energy efficient lighting	1994	UNEP, Lund University	C	R, C, I, Other	2010	2010	Res'l: 10-40% Com'l: 12-36% Ind'l: 25-41%	Various combinations of standards and DSM; based on supply curve analyses.	By subsector	Neg.	No	Savings measured vs. "constant efficiency" baselines.
USA	Residential Lighting: Use and Potential Savings	1996	US Department of Energy, Energy Information Administration	R	R	Overnight	Overnight	35%	Replace 4 incandescent lamps per home	Extensive survey		No	
USA	Lighting Market Sourcebook	1997	Lawrence Berkeley National Laboratory	R, C	R, C	2010	2010	67%, ~40%	Supply curve analyses	Very extensive		No	
USA	. "Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings	1992	Lawrence Berkeley National Laboratory	R, C	R, C	2030	2030	21%-56%; 35%-64%	A: Minimum Life-cycle cost; B: Research & Development	Extensive	Extensive	Yes	Includes separate analysis of savings from standards, by technology type.

Figure 1. Global ighting electricity generation by sector.

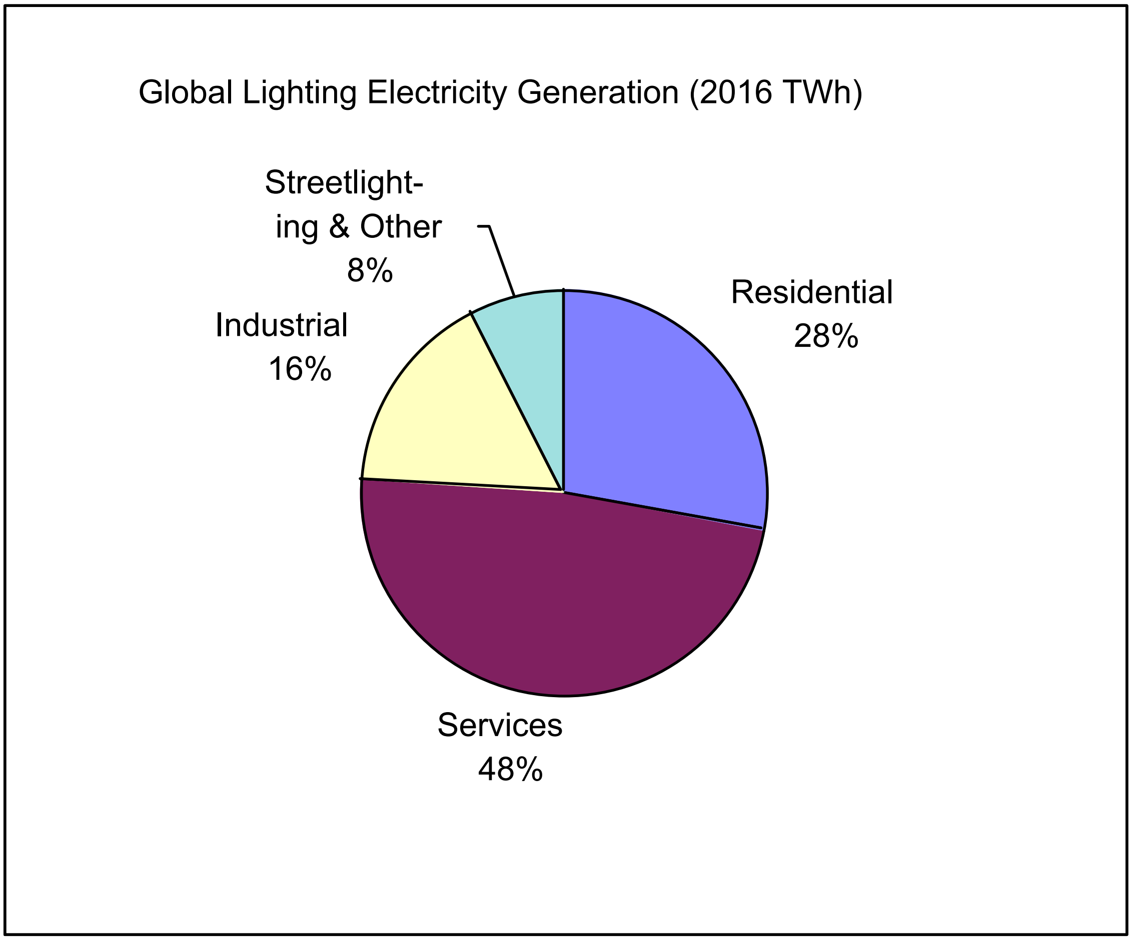


Figure 2. Per-capital lighting energy use versus GDP per capita for 41 countries.

Figure 2a-e. Lighting electricity use vs. per-capita GDP: (a) Total, (b) Residential, (c) Services, (d) Industrial, (e) Street Lighting & Other.

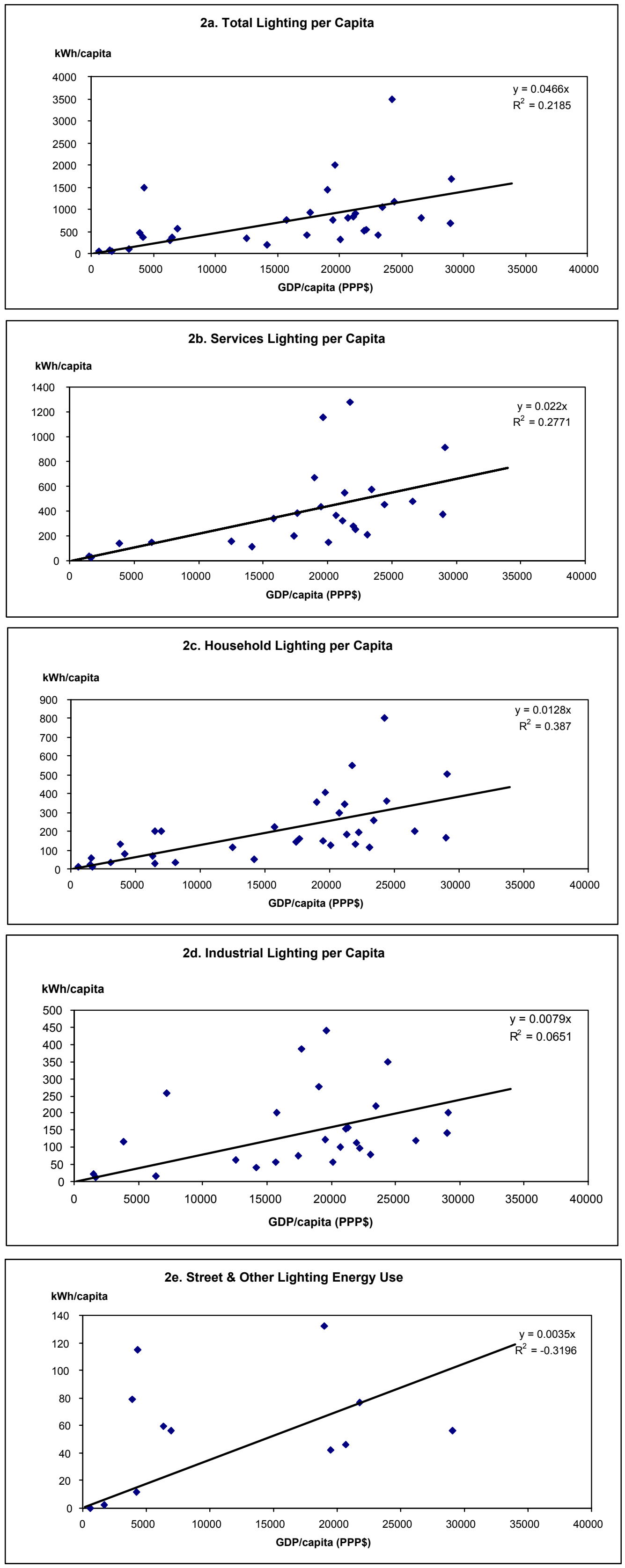


Figure 3. Range of lighting's share of total sectoral electricity use.

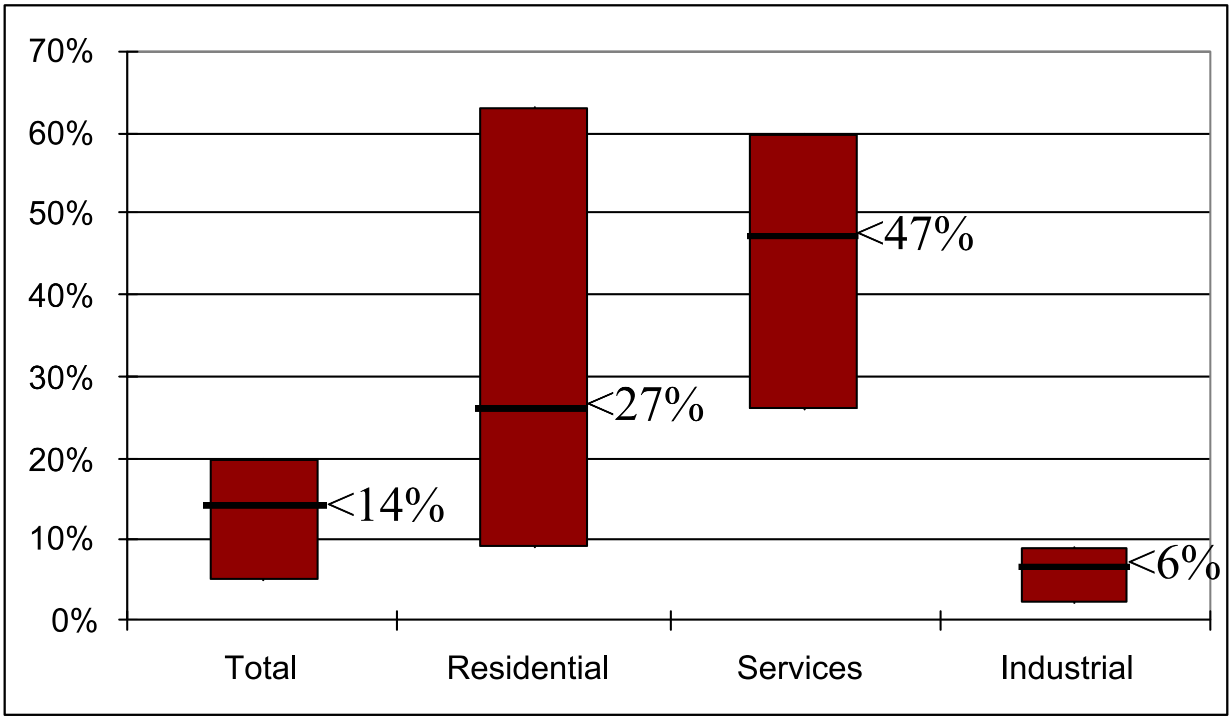
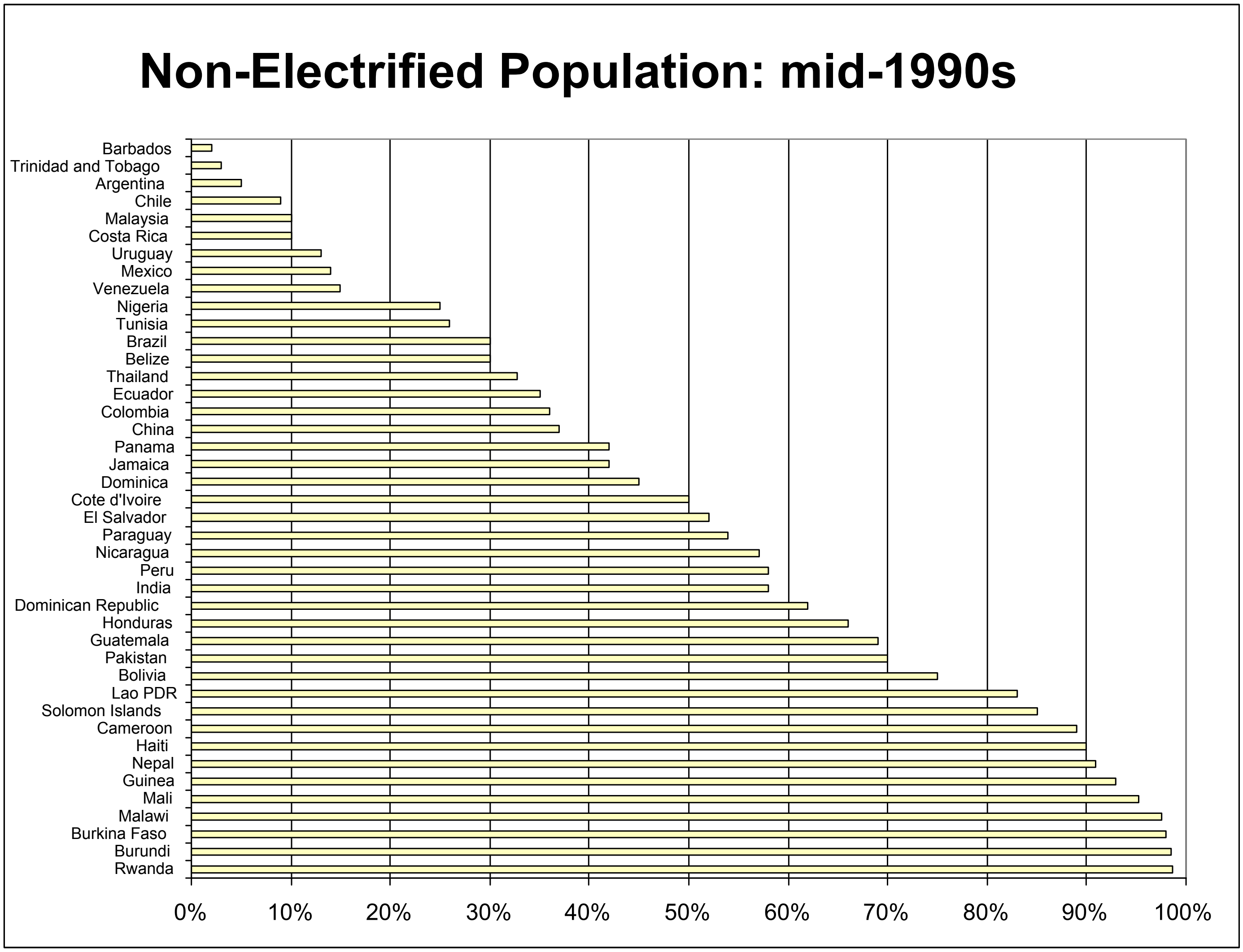


Figure 3. Electric incandescent bulb converted to a fuel-based lamp. Ghana marketplace (Photo credit: Rick Wilk).

Figure 5. Electric lighting in Europe, Africa, and the Middle East from space (NOAA 2000).

Figure 6. Electrification rates vary widely across the developing world (Mills 2002).



Page 7. Comparison of energy cost and services for electric versus-fuel-based lighting.