Title

Residential Use of Kerosene in Low- and Middle-Income Countries: Pollutant Emissions, Markers of Pollution, Drivers and Impacts

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Residential Use of Kerosene in Low- and Middle-Income Countries: Pollutant Emissions, Markers of Pollution, Drivers and Impacts

By

Nicholas Loren Lam

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requirements for the degree of
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in the
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ABSTRACT

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Household energy transitions in low and middle-income countries can play an important and often immediate role in improving human welfare in various dimensions. Residential use of kerosene, particularly as a lighting fuel in inefficient lamps, is one such energy use with the potential for significant improvements and benefits. I present measurements and analyses investigating characteristics of kerosene use, pollutant emissions from its use for household lighting and how distal drivers affecting price and access to electricity influence household consumption. Towards informing household air pollution assessment methodologies, a comparison of markers of complex pollutant mixtures is performed in the context of residential sources of combustion in Nepal.

Laboratory and field measurement showed that 7-9% of kerosene consumed by widely used simple wick lamps is converted to carbonaceous particulate matter that is nearly pure black carbon. Combined with estimates of bottom-up fuel consumption from survey-based estimates of user prevalence, these high emission factors increase previous black carbon emission estimates from kerosene by 20-fold, to 270 Gg/year (90% uncertainty bounds: 110, 590 Gg/year). Applying consumption and lighting device stock estimates from a recent UN assessment approximately doubles the central emissions estimate. Estimated global BC emissions from kerosene lighting sources are approximately one eighth of residential biomass BC emissions and one sixth of those from diesel. As a source, the net effect of pollutant emissions from kerosene lamps on climate would be positive (warming) given the relatively small cooling effect of co-emitted pollutants.

Indoor area measurements during operation of cooking and lighting appliances indicated that trends in polycyclic aromatic hydrocarbons and elemental carbon did not always reflect trends in standard markers of pollution, suggesting that their use as supplemental markers could provide added information. The most pronounced difference was observed from area concentrations during use of the sawdust stove, where total PAH concentrations were measured to be three times greater than from the second highest PAH source, the traditional biomass-burning chulo stove, but sawdust stove $PM_{2.5}$ concentrations were three times lower than from the chulo. Kerosene stove measurements showed average retene concentrations to be ten times higher than from the highest

biomass source, adding to existing skepticism over the use of retene as a source marker of softwood combustion.

From an analysis of residential kerosene use in India, lighting was found to account for over 60% of residential kerosene consumption. The electrified household population constituted an approximately equal share of kerosene demand as the non-electrified household population. Impacts resulting from kerosene lighting activities were also substantial, providing a potential opportunity to improve population welfare while also alleviating economic burdens associated with government subsidies. Reductions in ambient primary $PM_{2.5}$ resulting from the abatement of kerosene as a lighting source were estimated to avert between 0.27-1.6 million years of life lost in 2030. Early $PM_{2.5}$ control costs to replace kerosene with pico-solar lighting devices were estimated to yield a net savings of $3.5 billion in 2030, principally due to reductions in kerosene purchases. Kerosene demand for lighting was found to be highly price sensitive, so that in a scenario in which current subsidies are phased out by 2030, kerosene demand drops by 97% compared to the Baseline. The economic inefficiency implied results in an estimated deadweight loss from the kerosene subsidy of $950 million in 2005, with over three quarters attributed to its use as a secondary lighting source. The most effective measures for reducing kerosene burden would be those that address use as a secondary lighting fuel.

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1.0 Chapter 1

Introduction & Background

1.1 Introduction and Background

In 2010, an estimated 2.8 billion people in developing countries relied on biomass for cooking (*1*) and 1.2 billion were without access to electricity (*2*). A likely greater but uncertain number experienced frequent electricity supply interruptions. In the absence of reliable access to the cleaner energy sources more readily available in developed countries, households in low and middle-income countries often rely on fuels and technologies that are inefficient and polluting to meet daily energy requirements.

Improvements to household energy sources are often accompanied by significant co-benefits, ranging in scale from household-level (e.g. health, air quality, time savings) to regional (e.g. outdoor air quality, economic) and global (e.g. climate change) (*3*). As a result, household energy transitions can play an important and immediate role in improving human welfare through reductions in the global burden of disease (*4*) and improving the environment (*5-7*). Improving our understanding of the impacts and drivers of household energy choice from various dimensions can also provide the necessary evidence for developing more informed policy decisions, and interventions that more effectively mitigate and prevent residential energy-related burdens.

This body of work aims to fill some the gaps in the understanding of household energy use, drivers and impacts by focusing on components of household energy that have received less attention to-date: kerosene use in developing countries and its use as a residential lighting fuel. Expanding what is typically encompassed in household energy assessments and interventions may also provide new insights and synergies that can strengthen future interventions.

1.1.1 Residential Kerosene Use in Developing Countries

In many low- and middle-income countries, kerosene (paraffin, kerosine) has become a common fuel for meeting household energy service needs. It has a relatively high calorific value relative to solid fuels, and is also easier to store in houses and distribute than more efficient alternatives, such as liquefied petroleum gas (LPG) and electricity. For regions without electricity or low reliability, it is among the few energy sources that can be used for lighting. It has thus traditionally been highly subsidized by many governments in an attempt to support use by the poor.

Used in developing-country households, kerosene is generally a transition fuel for cooking, filling a space between traditional biomass and solid fuels, and “cleaner” alternatives (e.g. LPG, electricity). As opposed to being a primary cooking fuel, kerosene is more often used as a secondary energy source to supplement fuels on opposite ends of the “energy ladder” (*8, 9*). A recent study observed two categories of kerosene cooking households - “economy users” and “last resort users” (*10*). Both groups preferred LPG, however they used kerosene when fuel prices made it economically favorable (economy-users) or during LPG shortages (last-resort). As might be expected, the former group was more common if households were poorer, while the latter was more reflective of wealthier households. In rural communities, where residential biomass cooking is more prevalent than liquid-fueled cooking, kerosene is often used sparingly to complete short cooking tasks (e.g. making tea).

As a lighting fuel, kerosene is believed to be a predominant source of light for the 1.5 billion households without electricity access and the greater but more uncertain number that experience frequent electricity supply interruptions (*11*). Like residential cooking, anecdotal accounts indicate that lighting is also prone to energy stacking – the use of multiple fuels or technologies to meet the same energy-related task. Thus, despite electricity connection, kerosene or other fuel-based light sources (e.g. candles, LPG) may be used as a supplement if electricity outages are frequent (*12*). Co-benefits of more effective lighting options have motivated several large-scale programs, including the World Bank and IFC Global Lighting initiative (Lighting Africa, Lighting Asia), the UNEP En.Lighten initiative, and TERI's Lighting a Billion Lives program in India.

1.1.2 Kerosene Fuel Properties

With diesel, kerosene is one of the middle distillates (boiling temperature between 204-300^{o}C) of the petroleum refining process. Produced originally from coal ("coal oil"), but later from the fractional distillation of petroleum oil, kerosene is a transparent liquid fuel, with a mixture of hydrocarbon chains between 6-16 carbon atoms in length. The American Society of Testing and Materials (ASTM) defines two kerosene grades, 1-K and 2-K, acceptable for household appliance use. Grades are designated by impurity content, particularly sulfur and aromatics, which reduces combustion efficiency and increases noxious emissions during combustion. 1-K ("low-sulfur") kerosene contains no more than 0.04% sulfur by weight; 2-K has no more than 0.30% sulfur by weight. ASTM considers 1-K as suitable for use in flueless appliances (e.g. portable heaters), while 2-K is suitable for flued appliances. Both grades are designated for use in "illuminating lamps" (*13*). Cleaner burning lamp oils (*14*), which are often not kerosene but higher petroleum cuts (e.g. 142 Flash), are not commonly available in developing countries. Unlike many biomass fuels, which are inherently benign prior to combustion, liquid kerosene contains numerous compounds that pose known health risks, including various polycyclic aromatic hydrocarbons (PAH) and benzene.

1.1.3 Pollutant Emissions

Few studies have examined characteristics of pollutants emitted from household kerosene appliances used in low- and middle-income countries. In this document, "emissions" refers the quantity of pollutant emitted per unit of work (e.g. joules) or primary energy (e.g. kg). Existing data suggest that device activity (e.g. stove or lamp), design (e.g. wick or pressure type kerosene lamp) and operator setting (e.g. wick height, fuel grade) influence the magnitude of emissions (*14-17*). The broader literature on kerosene, suggests that fuel composition may also influence emissions. For some pollutants, including fine particulate matter (PM), these emission determinants may vary emission rates between levels low to high risk to health and environment. For example, reported PM emission factors (EF_{PM}) from household cookstoves range from 0.2 (*16*) to 0.8 gPM/kg (*18*), a factor of 4, while emissions from wick-based lanterns vary by a factor of

10, from 4 (*15*) to 52 gPM/kg (*19*). Operated indoors, upper end emission values could result in indoor concentrations slightly above air quality guidelines to an exceedance by an order of magnitude (*20*).

Particulate matter has often served as a key marker of pollution and health risk in household air pollution studies. Like biomass and other combustion sources, the mean aerodynamic diameter of PM emitted by kerosene sources is less than 10 µm *(14, 16, 17)*. However, evidence suggests that compositional differences may exist. First, particles from kerosene tend to be darker than those from biomass. Like diesel used in trucks, the composition of kerosene can result in high emissions of large fractions of aerosol carbon as elemental carbon (EC) and black carbon (BC). Reported EC/PM_{carbon} mass fractions range from 0.79-0.95 for kerosene lamp sources (*19*) and upwards of 0.15 for stoves (*16*). By comparison, the EC/PM_{carbon} ratio for biomass combustion typically falls between 0.05-0.15. In addition to the direct health impact of particles, BC (and EC) are highly efficient at absorbing sunlight and thus important from the perspective of climate change mitigation (*21, 22*). Also, greater EC/PM_{carbon} fractions may be indicative of combustion conditions favoring the formation of other health-damaging pollutants such as polycyclic aromatic hydrocarbons.

1.1.4 Pollutant Health Risks & Exposure Assessment

Exposure to pollutants resulting from household combustion – household air pollution - is now a well-recognized risk factor and contributor to the global disease burden (*4, 23*). Much of the existing evidence is based on research on exposure to biomass and coal smoke from to cooking. Compared to household gas fuels in developed countries and solid fuels in developing countries, there have been few studies of either exposure or resulting impacts of household kerosene use, especially for lighting. Well-documented kerosene hazards are poisonings, fires and explosions. Less investigated are the risks of exposures to kerosene combustion products. As a result, many assessments that consider "household air pollution" impacts or mitigation strategies could be expanded to consider a larger body of household energy characteristics if sufficient evidence were available.

1.1.4.1 Pollutant Health Risks

While health burden is a central component of this dissertation, the embodied work does not explicitly quantify health risk estimates. A brief summary of health effects from kerosene pollutants is provided, however, to provide some background on the literature to date. A more in-depth literature review of kerosene health risks in low and middle-income countries can be found in a review article by the author and two committee members Michael Bates and Kirk Smith on this dissertation (*24*).

Emissions indicate that kerosene appliances produce health damaging pollutants at rates potentially posing health risk, however, epidemiology studies investigating the relationship between residential kerosene sources and health outcomes are few. This is especially true for lighting. Based on a review of the literature, it was concluded that there was evidence to suggest that emissions from kerosene appliances, particularly from kerosene cooking, may impair lung function, promote asthma, and increase infectious illness and cataract risks. However, only limited conclusions could be drawn given the inconsistency in study design quality and results. The few studies of respiratory cancer were inconclusive. However, since kerosene combustion produces known carcinogens, including polycyclic aromatic hydrocarbons and formaldehyde, it is likely that kerosene combustion products are at least weakly carcinogenic, even though the epidemiologic studies are presently insufficient to show this. Studies published after the review have reported associations between kerosene as a primary cooking fuel and increased risk of acute lower respiratory infections (*25*) and low birth weight (*26*), and are suggestive of increased risk of stillbirth (*27*). With the exception of two studies in Nepal (*28, 29*), one of which found a strong association with tuberculosis risk (*29*), there is a lack of published investigations of whether kerosene used as a lighting fuel may cause health effects.

1.1.4.2 Exposure Assessment

Exposure assessment in household energy studies is generally conducted using indicators or markers of pollution, such as self-reported use of a pollutant source, or objective measures of complex pollutant mixtures – specifically undifferentiated PM mass and carbon monoxide. A brief review of how such methods have been applied helps to identify some of the potential reasons for the current deficiency our understanding of residential kerosene risks, especially for lighting.

1.1.4.2.1 Survey-Based Measures of Exposure

As a fuel considered midway up the energy ladder, kerosene has historically been inconsistently classified across studies. When kerosene use has been examined as an exposure, it is usually in the larger context of household fuel use, particularly solid fuel use. In part, this may be because of the favorable way that kerosene is often viewed. Some international agencies have treated kerosene as a “clean” fuel (*30*). Among researchers, some have grouped it with LPG, natural gas, and electricity for data analysis purposes (*31*); others, have treated it as a “polluting fuel” and grouped it with fuels known to emit substantial quantities of pollution, such as coal and biomass (*32, 33*). This conflicting interpretation may help to account for apparently inconsistent research results--influenced by whether kerosene is combined with the reference (‘clean’) fuels in the data analysis or whether, in the data analysis, it is combined with the fuels under investigation. Depending on the actual health impacts of kerosene combustion emissions, such arbitrary decisions could lead to underestimates or overestimates of effects.

1.1.4.2.2 Markers of Pollution

Kerosene cooking and especially lighting sources may seem fairly innocuous by comparison to solid fuels – such as biomass and coal – especially when evaluating common performance metrics, such as particle mass emissions or nominal combustion efficiency. For example, “standard” markers of pollution applied in household air pollution studies – undifferentiated PM and carbon monoxide - suggest kerosene sources to be of low risk relative to solid fuels such as biomass and coal. A simple calculation not accounting for time activity would indicates that kerosene lamp users would need 12-14 hours of lamp exposure to receive the equivalent of an open fire exposure (**Section 6.1.1**). Carbon monoxide exposure equivalent durations would be on the order of days. Equivalent exposure durations would be even longer for cooking. This would seem to contradict some of the emerging epidemiological evidence linking residential kerosene use with health outcomes (*25-27, 29*). Several exposure-related issues may help to explain this discrepancy.

The level of human exposure is determined by pollutant concentrations but modified by how the user interacts with the device, particularly proximity and duration. There is some evidence, for example, which suggests that personal exposure to PM among kerosene-cooking households can be similar to that resulting from wood, such that the ratio of personal and environmental PM concentrations was greater among kerosene users (*8, 34*). Saksena and colleagues attributed this effect to kerosene-using cooks spending more time in close proximity to the stove relative to biomass-using cooks. The proximity of an individual to the pollutant emissions source may also change the exposure concentration, and these variations in micro-environmental concentrations may not be captured using fixed area samplers. Proximity effects are often suggested for lighting sources, although several studies have indicated that the thermal plume of lamp emissions may help to attenuate differences between personal- and area-level measurements (*17, 35*). Overall, there are too few field-based studies to make a conclusion about the importance of proximity.

Health effects may also be influenced by the toxicity of the pollutant mixture, which is commonly summarized using markers of pollution, such as $PM_{2.5}$. This discrepancy between markers and health risk may be indicative of differences in the toxic potency of complex pollutant mixtures. For example, kerosene, like diesel, contains aromatic compounds (e.g. naphthalene) that can promote the formation of gas and particle-phase polycyclic aromatic hydrocarbons (PAHs) - immuno-compromising compounds (*36*) and pre-cursors to the formation of black carbon (BC) and elemental carbon (EC) (*37*). This compositional characteristic of kerosene is distinguishing from biomass fuels and may explain the greater propensity for kerosene (like diesel) to emit larger fractions of its aerosol particulate matter as black carbon (*19*). It also supports observations in the environmental literature of high correlations between BC or EC and PAH in air (*38*) and water (*39, 40*). A recent meta analysis using urban air pollution data from US cities found that risk estimates using BC, a marker for diesel in urban centers, yielded significantly higher risk estimates than undifferentiated PM (*41*). Authors conclude that the additional information from BC merits its addition as a pollutant marker in studies investigating primary combustion. Sahu et al. (2011) posited that potential differences in PM size distribution; specifically that the smaller median particle size emitted by a kerosene stove relative to traditional biomass stove, could yield lower mass-based concentrations but greater reactive surface area (*42*).

1.1.5 Upstream Drivers: Subsidies

I now step away from issues of pollutants and up the environmental pathway to discuss the upstream drivers that have made kerosene a relevant fuel source in the household energy sector. Residential use of kerosene and other refined and processed fuels presents economic considerations that are more pronounced than for many biomass fuels. A particularly relevant topic is the use of fuel subsidies as a means to increase economic access for a greater proportion of the population. India, as one example, is currently struggling with reducing the burden of kerosene subsidies introduced over half a century ago, but also maintaining lighting energy for non-electrified households. Also, as programs begin to look towards cleaner energy options, consideration of clean processed energy sources (e.g. LPG, electricity) will likely become of greater importance, as will strategies to finance access.

Over the last several decades, continued use of kerosene in the residential sector has only been sustained through national subsidies. While subsidy programs are often intended as redistribution mechanisms to improve access and quality of life for poor households, programs in practice are often inefficient and thus highly criticized. In India, for example, the cost to oil producers for providing subsidized kerosene intended for residential lighting and cooking was estimated at over $7 billion in 2013. Large-scale subsidies are also difficult to enforce and can lead to "leakage" – diversion to sectors and applications that are not intended targets of the subsidy. Several studies in India have revealed that as much as 30-40% of subsidized kerosene are never consumed by their intended populations (*10, 43*), and may not actually be of appreciable benefit in terms of economic savings (*10*). Such programs may be politically difficult to eliminate, potentially distorting long-term consumption patterns and hindering progression towards more efficient technology and resulting in dependence and economic welfare impacts (e.g. deadweight loss) (*44, 45*). In the case of kerosene, impacts to health and environment may add a considerable social cost to the subsidy, although no study to date has explored this.

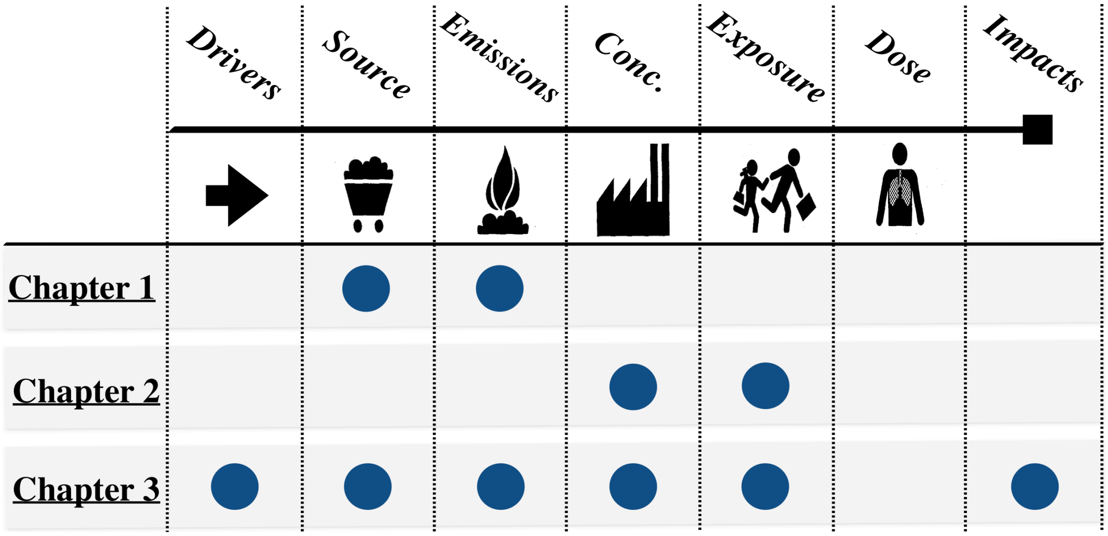
Economic burdens resulting from household energy subsidies have prompted efforts to limit, re-design, and entirely remove their use (*43, 46*). There is, however, little known about how subsidy reductions might impact populations welfare, and how services formerly met using subsidized fuel will continue to be met when greater financial barriers to the fuel exist. In Indonesia, for example, replacement of the kerosene subsidy beginning in 2005 was coupled with a less costly LPG subsidy, unconditional cash transfers, and one time gifts of an LPG stove and gas cylinders, with apparent great success in moving most households away from kerosene (*46-48*). Similar issues still exist in India and much of Sub-Saharan Africa, although existing data indicates that lighting, rather than cooking, is the primary end-use (*10, 49, 50*).

1.2 Dissertation Structure & Study Aims

This dissertation is divided into five parts. The current chapter provides a brief framing and overview of topics and literature underlying the motivation for subsequent chapters. Three chapters follow covering selected dimensions of kerosene as a household energy fuel. The fifth and final chapter is a summary and discussion of future directions for this research.

A generalization of the widely used Environmental Health Pathway provides a useful and relevant framework for which to contextualize material and themes presented within Chapters 2-4. Using the first version for household energy developed by Smith (*51*), the framework depicts six steps representing the progression from an energy source ("primary energy") to a final health effect: source, emission, concentration, exposure, dose, and health effect. The number of steps linking source and effect often varies by context or individual interpretation.

The adaptation of the pathway used to frame this work adds some flexibility to illustrate impacts which are not directly on health, but stem from household energy choices, such as climate impacts and economic welfare, and determinants of the fuel use, such as policy drivers or access to alternative energy sources. This generalization is likely a simplification when considering all issues associated with household energy, but is a reasonable representation for what is covered in this body of work.



	Drivers	Source	Emissions	Conc.	Exposure	Dose	Impacts
Chapter 1		●	●				
Chapter 2				●	●		
Chapter 3	●	●	●	●	●		●

Figure 1.1. Adaptation of the Environmental Health Pathway presented by Smith (*51*), indicating themes and subjects covered in Chapters 2-4 of the dissertation.

1.2.1 Chapter 2

Pollutant Emissions from Kerosene Lighting Devices: Laboratory and Field-Based Emission Factors and Global Emission Rates

Measure particulate matter ($PM_{2.5}$), particulate carbon (black carbon, organic carbon), carbon monoxide and carbon dioxide emission factors of typical kerosene lighting devices used in households within low- and middle-income countries. Compare differences in laboratory- and field-based measurements, and across lamp operational settings. Estimate global and regional black carbon emission rates based on emission factor results and a constructed fuel consumption inventory for kerosene lighting.

1.2.2 Chapter 3

Area Concentrations and Markers of Pollution: Household Cooking and Lighting Devices in Kaski District, Nepal

Measure environmental concentrations of a "standard" set ($PM_{2.5}$, TSP, carbon monoxide) and "supplemental" set (elemental carbon, organic carbon, 16 polycyclic aromatic hydrocarbons) of markers of pollution during operation of selected cooking and lighting devices used in households in Kaski District, Nepal. Evaluate whether pollutants in the supplement set provide any added information in terms of pollutant trends. Construct PAH diagnostic ratios to explore their potential for use as fuel or appliance indicators. Evaluate the performance of a direct-reading particle-bound PAH monitor across different aerosol mixtures by comparison against chemically determined PAH.

1.2.3 Chapter 4

Kerosene Lighting in Indian Households: Drivers of Demand and Impacts of Use

Perform an analysis of a nationally representative household survey of India to estimate the quantity and expenditure on kerosene used for primary and secondary lighting. Evaluate consumption and expenditure trends over population groups differing geographically (urban/rural), economically and by access to electricity supply (connection and reliability level). Use observed trends to inform the design of a demand model for estimating how changes in electricity connection, supply reliability, fuel price (subsidization level) and universal replacement with clean low-cost alternatives would alter demand trajectories. Under baseline and alternate futures scenarios, evaluate how changes in kerosene lighting alter pollutant emissions, and years of life lost due to exposure to outdoor primary $PM_{2.5}$. Quantify the economic inefficiency of the kerosene subsidy as a primary and secondary lighting fuel (deadweight loss) and the social cost of climate altering pollutants.

1.3 Contributions of the Dissertation

This dissertation combines primary field and laboratory measurements with secondary data sources to provide an in-depth and multifaceted assessment of impacts and characteristics of residential kerosene use in developing countries, especially as a lighting fuel.

Chapter 2 presents the first global estimates of pollutant emissions from the use of kerosene as residential lighting fuel. In the process, it presents an evaluation of characteristics required for including domestic lighting within pollutant and energy inventories, including survey-based estimates of user prevalence, fuel consumption, and pollutant emission factors.

Chapter 3 focuses on the potential benefit of expanding types of pollutant markers used in household air pollution studies. It provides the first comparison between typical markers of pollution and lesser-used PAH and EC markers over several household appliances. It reports on the sensitivity of a direct reading PAH monitor (PAS 2000CE) to various complex pollutant mixtures, by comparing its response to chemically speciated PAH concentrations. Finally, it explores the use of PAH measurements to construct diagnostic ratios for distinguishing fuels and appliances.

Chapter 4 provides the first in-depth assessment of historic and future trends in residential kerosene consumption for lighting in India. It attempts to link use of kerosene for lighting with various drivers and household characteristics, such as expenditure, geography, fuel price, electricity connection and electricity reliability. Exploratory impact estimates are provided from health, environmental and economic perspectives. The importance of secondary user populations on fuel consumption and impacts is reported when possible. I explore how future changes in fuel price, electricity access and supply, and replacement with clean technology might influence kerosene consumption and its associated downstream impacts.

1.4 References

1. S. Bonjour, H. Adair-Rohani, J. Wolf, N. Bruce, S. Mehta, A. Pruss-Ustun, M. Lahiff, E. A. Rehfuess, V. Mishra, K. R. Smith, Solid fuel use for household cooking: country and regional estimates for 1980-2010. *Environ Health Perspect* **121**, 784-790 (2013).
2. Sustainable Energy For All, "Global Tracking Framework," (2013).
3. K. R. Smith, A. Woodward, D. Campbell-Lendrum, D. Chadee, Y. Honda, Q. Liu, J. Olwoch, B. Revich, R. Sauerborn, "WGII AR5 Human health: Impacts, adaptation, and co-benefits," (IPCC, 2014).
4. S. S. Lim, T. Vos, A. D. Flaxman, G. Danaei, K. Shibuya, H. Adair-Rohani, M. Amann, H. R. Anderson, K. G. Andrews, M. Aryee *et al.*, A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **380**, 2224-2260 (2012).
5. D. Shindell, J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes *et al.*, Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335**, 183-189 (2012).
6. N. Unger, T. C. Bond, J. S. Wang, D. M. Koch, S. Menon, D. Shindell, S. Bauer, Attribution of climate forcing to economic sectors. *Proc. Nat. Acad. Sci. USA* **107**, 3382-3387 (2010).
7. T. C. Bond, E. Bhardwaj, R. Dong, R. Jogani, S. Jung, C. Roden, D. G. Streets, S. Fernandes, N. Trautmann, Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochemical Cycles* **21**, (2007).
8. K. R. Smith, M. G. Apte, M. Yuquing, W. Wongsekiarttirat, A. Kulkarni, Air pollution and the energy ladder in Asian cities. *Energy* **19**, 587-600 (1994).
9. O. R. Masera, B. D. Saatkamp, D. M. Kammen, From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development* **28**, 2083-2103 (2000).
10. N. D. Rao, Kerosene subsidies in India: When enery policy fails as social policy. *Energy for Sustainable Development* **16**, 35-43 (2012).
11. E. Mills, The specter of fuel-based lighting. *Science* **308**, 1263-1264 (2005).
12. I. H. Rehman, P. Malhotra, R. C. Pal, P. B. Singh, Availability of kerosene to rural households: a case study from India. *Energy Policy* **33**, 2165-2174 (2005).
13. ASTM, "Standard specification for kerosine D3699," *D3699-08* (ASTM International, West Conshohocken, Pennsylvania 2008).
14. C. Fan, J. Zhang, Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures. *Atmos. Environ.* **35**, 1281-1290 (2001).
15. S. Schare, K. R. Smith, Particulate emission rates of simple kerosene lamps. *Energy for Sustainable Development* **2**, 32-35 (1995).
16. G. Habib, C. Venkataraman, T. C. Bond, J. J. Schauer, Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels. *Environ Sci Technol* **42**, 8829-8834 (2008).

17. J. Apple, R. Vicente, A. Yarberry, N. Lohse, E. Mills, A. Jacobson, D. Poppendieck, Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air* **20**, 399-411 (2010).
18. J. Zhang, K. R. Smith, Y. Ma, S. Ye, F. Jiang, W. Qi, P. Liu, M. A. K. Khalil, R. A. Rasmussen, S. A. Thorneloe, Greenhouse gases and other airborne pollutants from household stoves in China: A database for emission factors. *Atmospheric Environment* **34**, 4537-4549 (2000).
19. L. W. A. Chen, H. Moosmuller, W. P. Arnott, J. C. Chow, J. G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, W. M. Hao, Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles. *Environ Sci Technol* **41**, 4317-4325 (2007).
20. WHO, "WHO air quality guidelines for particualte matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005`," (World Health Oganization Geneva 2006).
21. T. C. Bond, R. W. Bergstrom, Light absorption by carbonaceous particles: An investigative review *Aerosol Sci. Technol.* **40**, 27-67 (2006).
22. M. Z. Jacobson, Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *J. Geophys. Res.* **107**, 4410-4432 (2002).
23. C. J. L. Murray, M. Ezzati, A. D. Flaxman, S. Lim, R. Lozano, C. Michaud, M. Naghavi, J. a. Salomon, K. Shibuya, T. Vos *et al.*, GBD 2010: design, definitions, and metrics. *Lancet* **380**, 2063-2066 (2012).
24. N. L. Lam, K. R. Smith, A. Gauthier, M. N. Bates, Kerosene: a review of household uses and their hazards in low- and middle-income countries. *Journal of Toxicology and Environmental Health, Parth B: Critical Reviews* **15**, 396-432 (2012).
25. M. N. Bates, R. K. Chandyo, P. Valentiner-Branth, A. K. Pokhrel, M. Mathisen, S. Basnet, B. R. Shrestha, T. A. Strand, K. R. Smith, Acute lower respiratory infection in childhood and household fuel use in Bhaktapur, Nepal. *Environ Health Perspect* **121**, 637-642 (2013).
26. M. B. Epstein, M. N. Bates, N. K. Arora, K. Balakrishnan, D. W. Jack, K. R. Smith, Household fuels, low birth weight and neonatal death in India: the separate impacts of biomass, kerosene, and coal. *International Journal of Hygiene and Environmental Health* **216**, 523-532 (2013).
27. P. V. Lakshmi, N. K. Virdi, J. S. Thakur, K. R. Smith, M. N. Bates, R. Kumar, Biomass fuel and risk of tuberculosis: a case-control study from Northern India. *J Epidemiol Community Health*, (2010).
28. A. K. Pokhrel, K. R. Smith, A. Khalakdina, A. Deuja, M. N. Bates, Case–control study of indoor cooking smoke exposure and cataract in Nepal and India. *International Journal of Epidemiology* **34**, 702-708 (2005).
29. A. K. Pokhrel, M. N. Bates, S. C. Verma, H. S. Joshi, C. T. Sreeramareddy, K. R. Smith, Tuberculosis and Indoor Biomass and Kerosene Use in Nepal: A Case-Control Study. *Environ Health Perspect* **118**, (2010).
30. UNDP/ESMAP, "India: Access of the poor to clean household fuels. ," (2003).

31. T. Melsom, L. Brinch, J. O. Hessen, M. A. Schei, N. Kolstrup, B. K. Jacobsen, C. Svanes, M. R. Pandey, Asthma and indoor environment in Nepal. *Thorax* **56**, 477-481 (2001).
32. N. S. Gharaibeh, Effects of indoor air pollution on lung function of primary school children in Jordan. *Annals of Tropical Pediatrics* **16**, 97-102 (1996).
33. J. Wichmann, K. Voyi, Influence of cooking and heating fuel use on 1–59 month old mortality in South Africa. *Maternal and Child Health Journal* **10**, 553-561 (2006).
34. S. Saksena, P. Singh, R. K. Prasad, R. Prasad, P. Malhotra, V. Joshi, R. Patil, Exposure of infants to outdoor and indoor air pollution in low-income urban areas: A case study of Delhi. *J Expo Anal Environ Epidemiol* **13**, 219-230 (2003).
35. C. Furukawa, Brown University, Providence, RI (2012).
36. K. Nadeau, C. McDonald-Hyman, E. M. Noth, B. Pratt, S. K. Hammond, J. Balmes, I. Tager, Ambient air pollution impairs regulatory T-cell function in asthma. *Journal of Allergy and Clinical Immunology* **126**, 845-852.e810 (2010).
37. H. Richter, J. B. Howards, Formation of polycyclic aromatic hydrocarbons and their growth to soot - a review of chemical reaction pathways. *Progress in Energy and Combustion Science* **26**, 565-608 (2000).
38. S. Tang, R. Johnson, T. Lanni, W. Webster, T. Tagliaferro, J. Munn, C. Barnes, D. Barnes, K. Newkirk, D. Rivenburgh *et al.*, "Monitoring of PM-bound Polycyclic Aromatic Hydrocarbons from Diesel Vehicles by Photoelectric Aerosol Sensor (PAS)," (New York Department of Environmental Conservation, New York, 2001).
39. W. A. Thorsen, G. W. Cope, D. Shea, Bioavailability of PAHs: effects of soot carbon and PAH source. *Environmental Science & Technology* **38**, 2029-2037 (2004).
40. T. Agarwal, T. D. Bucheli, Is black carbon a better predictor of polycyclic aromatic hydrocarbon distribution in soils than total organic carbon ? *Environmental Pollution* **159**, 64-70 (2011).
41. N. A. H. Janssen, G. Hoek, M. Simic-lawson, P. Fischer, L. V. Bree, H. Brink, M. Keuken, R. W. Atkinson, H. R. Anderson, B. Brunekreef *et al.*, Review Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM 10 and PM 2 . 5. **119**, 1691-1699 (2011).
42. M. Sahu, J. Peipert, V. Singhal, G. N. Yadama, P. Biswas, Evaluation of mass and surface area concentration of particle emissions and development of emissions indices for cookstoves in rural India. *Environ Sci Technol* **45**, 2428–2434 (2011).
43. B. V. Shenoy, "Lessons learned from attempts to reform India's kerosene subsidy," (International Institute for Sustainable Development (IIST), Geneva, Switzerland, 2010).
44. S. Commander, "A guide to the political economy of reforming energy subsidies," *Policy Paper Series* (IZA, Bonn, Germany, 2012).
45. L. W. Davis, in *Working Paper,* B. University of California, Ed. (Berkeley, CA, 2014).
46. H. Budya, M. Y. Arofat, Providing cleaner energy access in Indonesia through the megaproject of kerosene conversion to LPG. *Energy Policy* **39**, 7575-7586 (2011).

47. C. Beaton, L. Lontoh, "Lessons Learned from Indonesia's Attempts to Reform Fossil-Fuel Subsidies Subsidies," (Winnipeg, Canada, 2010).
48. R. K. Koshala, M. Koshal, R. G. Boyd, H. Rachmany, Demand for kerosene in developing countries: A case of Indonesia. *Journal of Asian Economics* **10**, 329-336 (1999).
49. S. Desai, R. V, NCAER. (Inter-university Consortium for Political and Social Research Ann Arbor, 2009).
50. Y. Nagai, Technical University of Vienna, Vienna (2014).
51. K. R. Smith, *Biomass fuels, air pollution, and health: A global review*. (Plenum Books, New York, 1987).

2.0 Chapter 2

Pollutant Emissions from Kerosene Lighting Devices: Laboratory and Field-Based Emission Factors and Global Emission Rates

2.1 Background and Overview

One-fifth of the global population lacked access to electricity in 2009 (*1*) and many more had only intermittent access. Lack of clean energy for basic household needs leads to use of appliances and fuels with high pollutant emissions. Products of incomplete combustion from biomass and coal used in cookstoves affect not only household environments and human health (*2*) but also outdoor air pollution and climate (*3*). Lighting is another component of this household energy challenge, with millions of households still relying on simple liquid-fueled lamps, but relatively little is known of the associated environmental and health impacts.

2.1.1 Black Carbon and Household Energy

One environmental issue that has been linked with emissions from household-solid fuel burning is that of black carbon (BC) and climate change (*4*). BC is a product of incomplete combustion and one of the few components of atmospheric aerosol that absorbs light and heats the atmosphere, thereby contributing to climate warming (*5*). The most common measure of climate impact, termed radiative forcing, describes the change in Earth's net energy balance imposed by a single constituent or set of constituents at the top of the atmosphere (tropopause). Positive forcing is associated with average warming. During its short atmospheric lifetime, one kg of BC produces as much positive forcing as 700 kg of carbon dioxide (CO_2) does during 100 years (*6*). Some have proposed that reducing BC emissions could rapidly reduce this warming and prevent Earth's temperature from reaching dangerous levels (*7-9*), while simultaneously improving human health (*10*). Most sources of BC, however, also emit aerosol organic carbon (OC), which cools the Earth by reflecting sunlight (*11*) and increasing cloud brightness (*12, 13*). The net effect (warming or cooling) of particles from any source depends on how much of the emitted total aerosol carbon (TC) is BC (*14*). Thus, mitigating many BC sources may not actually reduce warming if their OC emissions are substantial.

2.1.2 Kerosene and Residential Lighting

Among households with limited access to electricity, kerosene (paraffin) is among the most common lighting fuels in developing countries because it is easily transported, stored, and affordable, due principally to government subsidies. It has been estimated that houses without electricity consume 77 billion liters of liquid fuels (mostly kerosene) to meet lighting requirements, corresponding to 190 million metric tonnes of CO_2 per year (*15*). Despite the existence of clean and efficient lamp designs, households often burn kerosene in locally constructed simple wick lamps, which consist of a rope or cloth wick extending from a metal or glass container (**Figure 2.1.1a**). Also common is the commercially manufactured, glass-shrouded "hurricane" wick lamp (**Figure 2.1.1b**). These lighting devices emit particulate matter (PM) (*16, 17*) that remains in the atmosphere for several days due to its small size (*17, 18*).

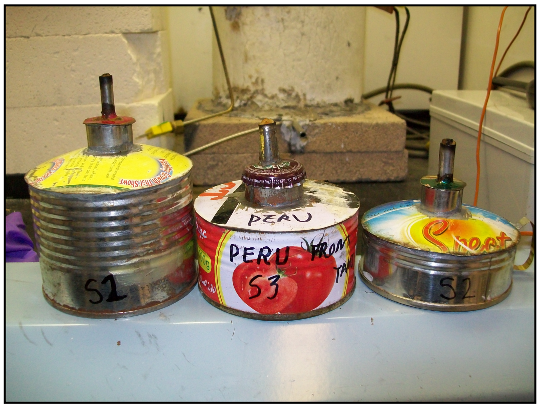


Figure 2.1.1a. Simple wick lamps

Figure 2.1.1b. Hurricane wick lantern

2.1.3 Study Objectives

There is little information on characteristics or impacts of residential lighting in the household energy literature. The health and climate impacts, and mitigation benefits, of pollutant emissions is among one of the topics receiving increased attention in the peer-reviewed literature and among policymakers, but has generally focused on residential cooking. Few studies or assessment have considered residential lighting in any capacity when assessing impacts of household energy, or more specifically household air pollution. One previous laboratory study has suggested that particulate emissions from hurricane-style kerosene lamps are mostly BC (about 80%), but in that study the lamps were deliberately operated at conditions unrepresentative of typical household usage (*19, 20*). Towards understanding the impact of lighting on pollutant emissions, specifically of black carbon, this study:

- Presents field and laboratory measurements of BC, OC, particulate matter (PM), carbon monoxide (CO) and carbon dioxide (CO_2) emission factors from kerosene wick and hurricane lamps.
- Estimates regional and global kerosene consumption for lighting activities in the residential sector – largely focusing on its use as a primary lighting source.
- Combines results from emission measurements and kerosene consumption to infer regional and global emission rates of black carbon.

2.2 Methods

2.2.1 Emission Measurement

In-field emissions were measured from simple wick lamps purchased and prepared by local residents in Southwestern Uganda. Field conditions ensure that the devices tested and their fuels are representative of actual practice, but measurements are made under challenging conditions without electricity, so that less controlled measurements are possible relative to laboratory testing. Therefore, to provide more robust results, repeated tests of simple wick lamps from Uganda and Peru, and sensitivity studies, were also performed in a laboratory setting at the University of Illinois at Urbana-Champaign.

2.2.1.1 Lamp Operating Conditions

For laboratory tests, a baseline lamp operating condition, based on field observations, consisted of a cloth wick at a height of 1-1.5 mm ("low"). Unless stated otherwise, laboratory tests were conducted using kerosene purchased in the USA (grade 1-K) and tested in triplicate. Sensitivity tests included replacing the cloth wick with a rope-style wick (also used in kerosene stoves), increasing the wick height to 3-4 mm ("high"), and burning kerosene imported from Uganda. Sensitivity tests in the lab were conducted in triplicate on one of the three simple wick lamps used for baseline testing. A hurricane lamp was also tested in the laboratory.

2.2.1.2 Emissions Sampling Systems

Emissions measured in real-time were carbon monoxide (CO), carbon dioxide (CO_2), and particle optical properties—light absorption and scattering. These real-time measurements were recorded every four seconds during tests lasting approximately one hour. In the field a modified Portable Emission Monitoring System (PEMS, Aprovecho Research Center, Cottage Grove, OR) measured CO (SS1128, Senko) and CO_2 (Telaire T6004, GE) using electrochemical and non-dispersive infrared (NDIR) sensors, respectively. The real-time particle scattering coefficient was measured with the PEMS PM sensor at a red wavelength (660nm). A Particle Soot Absorption Photometer (PSAP, Radiance Research, Shoreline, WA) measured absorption at three wavelengths of 467, 530 and 660 nm. For laboratory tests, CO_2 and CO concentrations were measured in real-time with a Li-COR 6252 (Li-COR Biosciences, Lincoln, NE) and Horiba AIA-220 (Horiba, Kyoto, Japan) non-dispersive infrared (NDIR) analyzer, respectively. Particle scattering was measured with an integrating nephelometer (M903, Radiance Research, Shoreline, WA) at a wavelength of 530 nm, and absorption was also measured with the PSAP. Measured scattering and absorption was used to calculate climate relevant characteristics of aerosols, including the single scattering albedo (SSA), mass scattering cross section (MSC), and mass absorption cross section of black carbon (MAC_{BC}). An enhancement in the laboratory system, which has been described and evaluated elsewhere (*21*) was an additional sample dilution using dry particle-free air (dilution ratio of about 3:1 for simple-wick lamps) to accommodate high particle concentrations and provide more accurate optical measurements. All real-time measurements (CO, CO_2, particle absorption and scattering coefficient) were converted to standard conditions (1 atm and 20 °C). Background CO and CO_2 concentrations, and particle scattering and absorption, were subtracted.

2.2.1.2.1 Laboratory Measurement System

Figure 2.2.1 provides an overview of the laboratory sampling system used to measure emissions from lamps; **Figures 2.2.2b** show the sampling rack and probe with lamp, respectively. Laboratory tests were conducted at the University of Illinois at Urbana-Champagne.

A multipoint dilution sampling probe (21) was used to extract the lamp emissions at a flow rate of 5 L/min. The probe sets include a 1.5 ft probe, four 6 in and four 2 in probes with decreasing hole size closer to the center. Dry, particle-free air was used as the diluent at a ratio of 2-3:1. After, the dilution CO_2 and CO concentrations were measured in real-time with a Li-COR 6252 (Li-COR Biosciences, Lincoln, NE) and Horiba AIA-220 (Horiba, Kyoto, Japan) non-dispersive infrared (NDIR) analyzers, respectively. Gas analyzers were calibrated with standard span gas (S.J. Smith Co., Decatur, IL) under sampling conditions. A second dilution step with dry particle-free air at a dilution ratio of 3:1 was required to prevent the overloading of the scattering coefficient signal of the integrating nephelometer (M903, Radiance Research, Shoreline, WA) operating at a wavelength of 530 nm. This instrument was calibrated before and after the experiment with dry particle free air (ZERO) and Coleman-grade CO_2 (SPAN). Parallel to the nephelometer a particle soot absorption photometer (PSAP, Radiance Research, Shoreline, WA) was operated at a flow rate of 0.2 L/min to measure the absorption coefficient at three wavelengths of 467, 530 and 660 nm. Flow rates through filter holders varied from 0.2-0.6 L/min. Methods for gravimetric and chemical filter analysis are presented in **Section 2.2.1.3**.

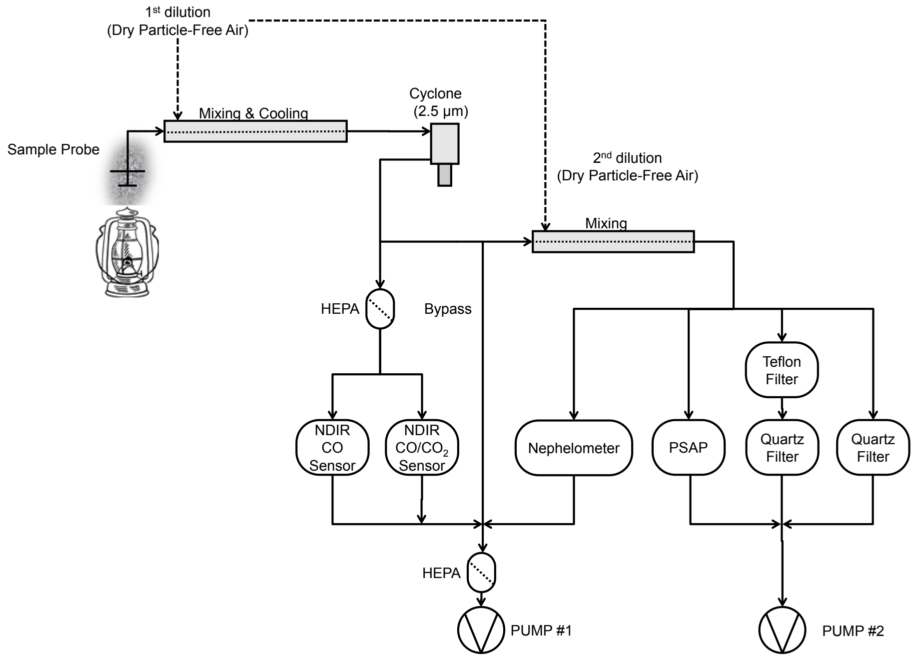


Figure 2.2.1. Laboratory emission sampling system schematic

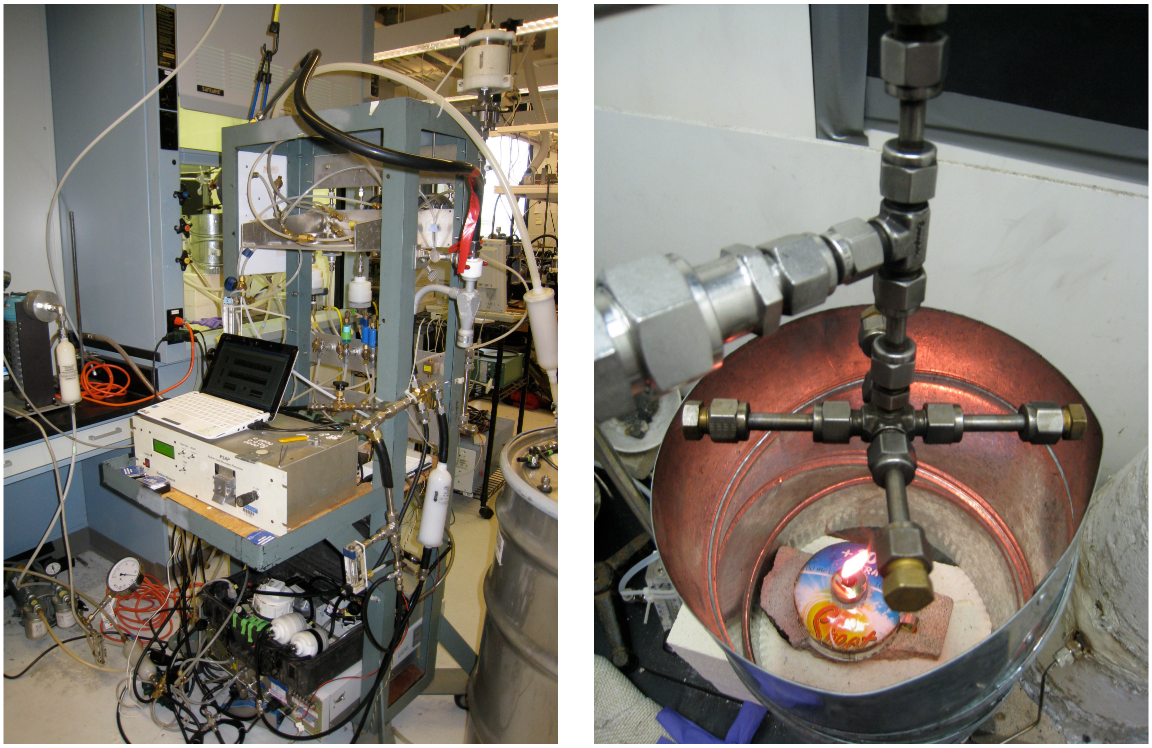


Figure 2.2.2a-b. Laboratory emissions system at the University if Illinois at Urbana-Champagne. Sampling rack (left) and sample probe with lamp (right).

2.2.1.2.2 Field Measurement System

Figure 2.2.3 presents a schematic of the sampling system used to measure emissions from lamps under field conditions. **Figures 2.2.4a-b** show the field sample system and sample probe, respectively. Samples were taken on an outdoor patio with lamps placed on the ground. A multipoint sampling probe was used to extract emissions at a flow rate of ~2 L/min. Real-time data were recorded every second.

CO and CO_2 sensors were calibrated with zero and span gases. The raw scattering signal from the PM sensor was calibrated with an integrating nephelometer (3563, TSI Inc., Shoreview, MN) to provide a particle scattering coefficient at red wavelength (660 nm). All calibrations were performed in the laboratory before the field campaign. Ambient temperature, pressure and relative humidity were recorded for each test, and were used to correct measured concentrations to standard conditions. Gravimetric analysis procedures for calculating mass, EC and OC were identical to those used in laboratory experiments (See **Section 2.2.1.3**).

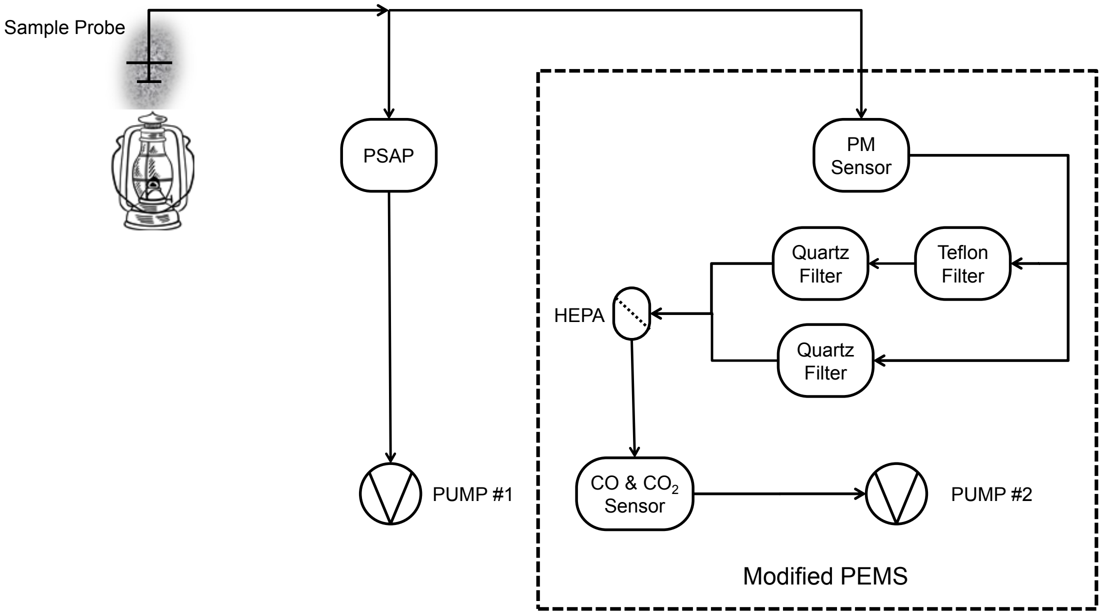


Figure 2.2.3. Field emission sampling system schematic

Figures 2.2.4a-b. In-field testing of kerosene lamps in Western Uganda (2010). Sample probe (left) and emissions train (right).

2.2.1.3 Filter Based Sampling

2.2.1.3.1 Gravimetric Sampling

Samples for $PM_{2.5}$ or PM_{TSP} mass and elemental (EC) and organic (OC) carbon analysis were captured on filter membranes integrated over the entire test. For laboratory tests, sample flow was passed through a micro-centrifuge (URG-2000-30EN, URG Corp, Chapel Hill, NC) with an aerodynamic cut-off diameter of 2.5 µm; no aerodynamic cut-off was applied in field measurements. Negligible PM was found in the centrifuge collector used in the laboratory; that is, much of the emitted PM had aerodynamic diameters smaller than 2.5 µm. Two filter holders (URG-2000-30RAF, URG Corp, Chapel Hill, NC) were used to collect filter samples for test-integrated mass measurements of PM, OC and EC. One filter holder contained a pre-baked 47mm quartz fiber filter (TISSUQUARTZ 2500QAT-UP, Pall). The other holder contained a 47mm Teflon filter (1.0 µm pore size, Fluoropore™ Membrane Filters, FALP04700, Millipore) upstream of another pre-baked quartz fiber filter. The Teflon filter was weighed before and after sampling to obtain PM mass using a microbalance (Cahn C-31, Thermo Electron Corp.) in a temperature and humidity controlled room after 24 hours of conditioning.

2.2.1.3.2 Elemental Carbon and Organic Carbon

Elemental carbon (EC), presented here as an equivalent to BC, and OC were measured on the quartz filters with a Sunset Laboratory OC/EC Analyzer (Sunset Laboratory, Tigard, OR) using the thermal-optical-transmittance method (TOT) (22). In the TOT method, filter transmittance is monitored during the whole procedure and used to correct for OC charring (pyrolysis). When such charring occurs, it is known to introduce uncertainties into the determination of EC. However, as shown in the results, little OC was present that could char. Under these circumstances, the division between elemental and organic carbon has little artifact, and the EC so determined is nearly equivalent to BC. The quartz filter downstream of the Teflon filter was used to account for organic vapor adsorption (23, 24). Field blanks were collected during field sampling and apparent mass was an average of six times lower than sampled filters ($p < 0.05$).

In the NIOSH TOT method, OC and carbonate carbon in the sample are first volatized in a pure helium atmosphere as the temperature is stepped to 890°C. The temperature is then reduced and oxygen-helium carrier gas is introduced. The temperature is then raised to 860°C in steps, when elemental carbon (here used as equivalent to black carbon) is evolved. An ideal temperature profiles is shown in **Figure 2.2.5**. All carbon evolving from the filter is reduced to methane, and measured with a flame ionization detector.

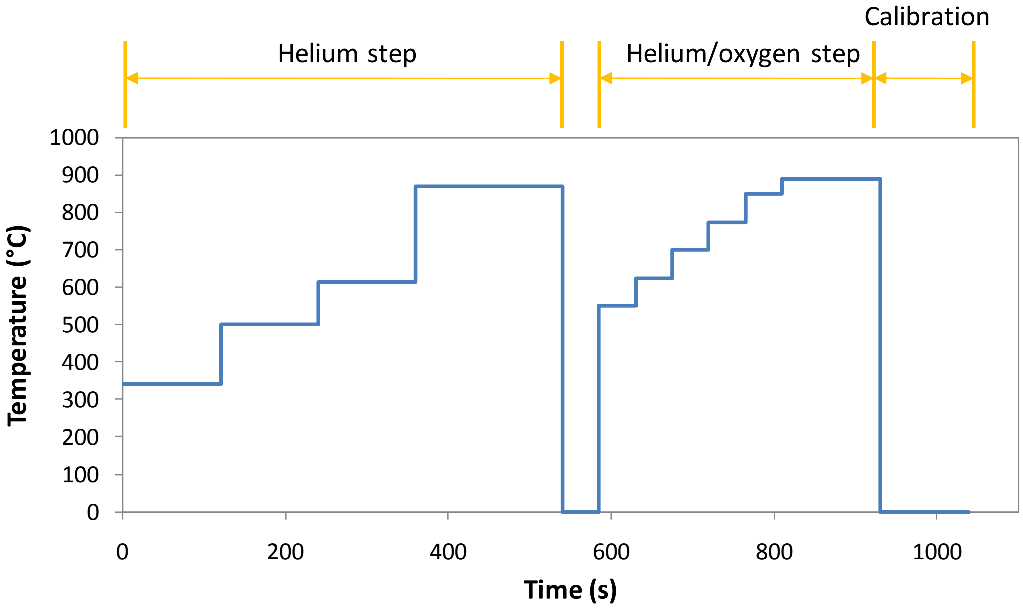


Figure 2.2.5. Temperature profile of NIOSH TOT method on the Sunset OC/EC analyzer

2.2.1.3.3 Aerosol Optical Properties

Data obtained from real-time measurements, sometimes combined with filter results, can be used to calculate test-averaged properties such as single scattering albedo (SSA), mass scattering cross section (MSC) and mass absorption cross section (MAC_{BC}). These parameters were calculated as:

$$SSA_{lab} = \frac{b_{sp,avg}}{b_{sp,avg} + b_{ap530,avg}}$$

$$SSA_{field} = \frac{b_{sp,avg}}{b_{sp,avg} + b_{ap660,avg}}$$

$$MSC = \frac{b_{sp,avg}}{C_{PM}}$$

$$MAC_{BC} = \frac{b_{ap530,avg}}{C_{BC}}$$

Where $b_{sp,avg}$ is the test-averaged scattering coefficient (530nm for the laboratory tests and 660nm for field tests, Mm^{-1}), $b_{ap530,avg}$ is the : test-averaged absorption coefficient (530nm, Mm^{-1}), $b_{ap660,avg}$ is the test-averaged absorption coefficient (660nm, Mm^{-1}), C_{PM} is the filter-integrated PM concentration for a test (g/m^3), and C_{BC} is the filter-integrated BC concentration for a test (g/m^3).

Single scattering albedo (SSA) is an optical characteristic of aerosol that describes the magnitude and sign of its direct radiative forcing. That is, SSA describes whether an aerosol is net absorbing or reflecting given a specific wavelength of light. Specifically, SSA is defined as the fraction of extinction of a given wavelength of light due to scattering, as opposed to absorption. Light scattering or absorption characteristics can be used to inform aerosol models, such as those used by climate models, to estimate the impact of pollutant emissions on Earth's energy balance. In practice, aerosol characteristics are often normalized by corresponding mass concentrations (e.g. MAC_{BC}, MSC_{PM}) for use in models, which often rely on emission inventories, which are expressed in mass units.

2.2.1.4 Emission Factor Calculation

Emission factors for PM, BC and OC (EF_{PM}, EF_{OC} or EF_{BC}) are expressed in units of g PM (OC or BC) per kg of kerosene burnt and determined with the carbon balance method (CBM). Several other methods for estimating emissions exist, however. In the following section, the CBM method is presented in detail, in addition to two other methods for quantifying pollutant emissions. Limitations and advantages are discussed.

2.2.1.4.1 Carbon Mass Balance (CBM)

This method assumes that all gaseous and particulate carbon present in a volume of sampled air came from the fuel that also produced the pollutants in that volume, so that emission factors can be calculated with a ratio between the two concentrations.

$$EF_{PM}(g_{PM}/kg\ Kerosene) = \frac{C_{pm}(g/m^3\ air)}{Fuel\ (kg/m^3\ air)} = \frac{M_{pm}/(Q_{PM} \cdot T)\ (g/m^3\ air)}{Fuel\ (kg/m^3\ air)}$$

Where, C_{pm} is the mass concentration, M_{PM} is the mass of PM on the filter as determined by the methods described previously, Q_{PM} is the flow rate through the filter, and T is the length of the sampling period. Emission factors of CO and CO_2 were determined in a similar way but used the test averaged CO or CO_2 concentration instead of C_{PM}. *Fuel* has the unit of kg kerosene consumed per cubic meter of air sampled (kg/m^3) and determined using the "carbon balance method", which uses the total gaseous and particulate carbon

(CO + CO$_2$ + EC + OC) emissions as a proxy for total fuel burnt. Carbon content of kerosene is approximately 85% (*25*). *Fuel* is calculated with the following equation:

$$Fuel\ (kg\ kero/m^3 air) = \frac{gas_{carbon}\left(\frac{m^3}{m^3 gas_{carbon}}\right) \cdot 0.499 \left(\frac{kgC}{m^3 gas_{carbon}}\right)}{0.85 \left(\frac{kgC}{kg\ kero}\right)}$$

One advantage of the CBM is the ability to obtain emission rates with low sampling flows and, hence, low power. Another advantage is the ability to sample sources for which containment within a hood would degrade the quantity, realism, or operation. This method has been used for measuring emissions from cookstoves (*21*), biomass burning (*26*), and vehicles (*27*). One limitation of the method is the need to obtain a representative sample across the exhaust plume, which was accomplish by using a sampling probe with 16 equal-flow ports. A potential inaccuracy compared with constant-volume sampling occurs if dilution or flow rates through the combustion device vary during the sampling period, but lamp combustion was quite stable.

2.2.1.4.2 Chamber/Well Mixed Room Method (WMR)

The chamber, or well-mixed room (WMR), method for calculating pollutant emissions is based on the premise that the concentration of a pollutant emitted into a room will follow a lognormal growth function. Assuming that the pollutant concentration, room volume and major acting removal mechanisms are known, the emission rate (e.g. gPM$_{2.5}$/minute) is the remaining unknown and can be solved for. This methodology assumes that pollutants are perfectly and instantaneously mixed, and that all significant loss mechanisms are first order and have known rates. As indicated by the calculation procedure, the WMR, like the CMB, is not a direct measure of emissions. The emission rate can be converted to an emission factor by dividing by the fuel consumption rate, often referred to as the burn rate (e.g. kg fuel/minute). Advantages of the WMR method are its simplicity, and that the method has a long and established history of use, especially in the context of measuring sources in indoor environments. WMR method can be described with the following function, using PM as an example:

$$C_t(mg\Big/m^3) = \frac{ER_{PM}\left(\frac{mg}{hr}\right)}{Q_{eff}\left(\frac{m^3}{hr}\right)} \times \left(1 - exp^{-\frac{Q_{eff}}{V} \cdot T}\right)$$

Where,

$$Q_{eff} = \sum_{i=1}^{n} \alpha_i V$$

Where Q_{eff} is the effective ventilation rate, the sum of all first order loss rates (α) expressed in terms of volumetric loss. At relatively high air exchange rates (> 4/hour), the first order loss rates for settling, deposition to surfaces (particles) and reaction (some gasses) would be expected to be several orders of magnitude lower than that of ventilation. *V* is the volume of the chamber, *t* is the time relative to the start, *ER* is the average emission rate (e.g. mg/min), and C_t is the instantaneous concentration at time *t*. As *t* approaches infinity, the quantity in the parentheses approaches unity and the function plateaus, resulting in a steady state concentration. In practice, the equation is re-arranged to solve for the ER.

An alternative calculation estimates the time weighted average concentration (C_{TWA}) over a specified time window (T_1 to T_2). This is especially useful when direct reading instruments (minute-by-minute measurements) are not available or when there is fluctuation in the emission rate such that instantaneous values may be less reliable.

$$C_{TWA} = \frac{ER_{PM}}{Q_{eff} \cdot (T_2 - T_1)} \cdot \left[T_2 + \frac{V}{Q_{eff}} exp^{-\frac{Q_{eff}}{V} \cdot T_2} - T_1 - \frac{V}{Q_{eff}} exp^{-\frac{Q_{eff}}{V} \cdot T_1} \right]$$

As with the instantaneous concentration, the time weighted estimate can be re-arranged to solve for the emission rate:

$$ER_{PM} = \frac{C_{TWA} \cdot Q_{eff} \cdot (T_2 - T_1)}{\left[T_2 + \frac{V}{Q_{eff}} exp^{-\frac{Q_{eff}}{V} \cdot T_2} - T_1 - \frac{V}{Q_{eff}} exp^{-\frac{Q_{eff}}{V} \cdot T_1} \right]}$$

2.2.1.4.3 Hood Capture Method (HCM)

The hood capture method is a direct measure of emissions but the most difficult to implement in-field. The HCM relies on capturing all emitted pollutants into a hood or ventilations system with known volumetric flow rate. Pollutant concentrations are measured via a sampling probe placed inside the emission stack. Assuming that that there are no fugitive emissions, or that fugitive emissions are minimal, the emission rate can be calculated as the product of the pollutant concentration (e.g. mg/m^3) and flow rate (m^3/min). Dividing by the fuel consumption rate yields an emission factor:

$$EF_{PM}(mgPM/kg\ Fuel) = \frac{C_{PM}(mgPM/m^3) \cdot Q(m^3/min)}{BR\ (kg\ Fuel/min)}$$

Few assumptions are needed for the HCM making it a very attractive method for testing under laboratory settings. There are, however, several major limitations. First is that it is often the least representative of actual user conditions. Since pollutants are immediately captured in a high volume stack, particles sampled from the stack may not be evolved to a point of being representative of indoor environments. Furthermore, deploying a hood in-field is logistically challenging and invasive. In addition to this modifying use behavior, high volume blowers required to capture emissions can also draw excess air into flames and alter combustion efficiency.

2.2.2 Fuel Analysis

Testing of kerosene composition was performed on samples purchased and produced in the USA and Uganda by Intertek Labs (Chicago, Illinois, USA). US samples were taken from the same fuel stocks burned in lamps tested in laboratory experiments. Ugandan fuel was purchased in Kampala, Uganda and shipped back to the US for testing. Ugandan kerosene had approximately five to six times the sulfur content and six times the particulate contamination (**Table 2.2.1**). Aromatic content was higher as were some trace elements, including calcium, silicon, and especially sodium, and zinc.

Table 2.2.1. Kerosene fuel composition

ASTM Method		Uganda	USA	Units
ASTM D4294	Sulfur Content	0.082	0.015	Wt %
ASTM D1319	Aromatics	18.8	16.1	Vol %
ASTM D482	Ash	<0.001	0.002	Wt %
ASTM D7111	Trace Elements			
	Calcium	0.12	< 0.10	mg/kg
	Silicon	1.40	0.1	mg/kg
	Sodium	0.50	0.41	mg/kg
	Zinc	2.00	< 0.10	mg/kg
ASTM D5452	Particulate	6.80	1.11	mg/L

2.2.3 Global BC emissions

Kerosene consumed in the residential sector may be used for lighting, cooking, or heating. To estimate the fraction of residential kerosene used for lighting (f_{light}), the annual consumption of kerosene for lighting was first estimated with "bottom-up" estimates in countries where the number of houses using kerosene for light is reported, or can be inferred with knowledge about households that lack access to electricity. Such data were available for several nations, including India, one of the largest residential kerosene users, nineteen countries in Africa, four in South East Asia, and ten in Latin America. Finally, the bottom-up estimates for each available country within a region was divided by the corresponding residential kerosene consumption reported by IEA (*28, 29*) to obtain an estimate of f_{light}. In turn, these values were extrapolated to the entire region. Additional data to constrain the consumption for lighting in India was also applied based on nationally representative household-level surveys. With the exception of India, analyses account only primary users of kerosene. The potential importance of secondary/backup users is explored in more detail within **Chapter 4**.

The following sections outline and discuss the calculation of each component of emissions (*EM*) from a single type of lighting device (e.g. simple wick, hurricane) in a given region. The device contributions are then summed. This process can be described as the product of five major factors:

$$EM = KERO \times f_{light} \times f_{device} \times EF_{device} \times f_{outdoor}$$

Where *KERO* is regional kerosene use in the residential sector in year 2005 from the International Energy Agency (IEA) *(28, 29)*, f_{light} is the fraction of residential kerosene consumption attributable to lighting demands (described below), f_{device} is the fraction of kerosene lighting accomplished with a particular lighting device. Lamps are assumed to be either simple wick or hurricane style, so that f_{device} for the two types sums to unity. Values of f_{device} for simple-wick lamps range from 0.25 in the Middle East to 0.8 in most of Asia. EF_{device} is the device-specific pollutant emission factor (e.g. EF_{BC}) taken from results presented here. $f_{outdoor}$ is the fraction that escapes outdoors, estimated at 0.89 with a 90% uncertainty range of 0.60 to 0.97 (**See 2.2.3.3**). Estimation procedures for components of f_{light} were based on observations as described in subsequent sections (**See 2.2.3.1**). Where f_{light} is greater than zero, it ranges from 0.01 in Southern Africa to 0.6 in Northern Africa. Emissions are calculated separately for simple wick lamps and hurricane lamps and then added to obtain total emissions from lighting. Uncertainties for each factor of EM were implemented in a Monte Carlo analysis assuming independence between parameters.

2.2.3.1 Fraction of Residential kerosene used for lighting (flight)

For each country with available and necessary data, a bottom-up estimate of kerosene consumption for lighting, $Kero_{est}$, was calculated as the product of five factors:

$$KERO_{est} = N_{house} \times f_{kero} \times N_{lamp} \times t \times BR \times 365$$

1. N_{house} : The number of households in the country
2. f_{kero} : The fraction of households reported or estimated to rely on kerosene for lighting (primary).
3. N_{lamp} : The estimated number of kerosene lamps in each household
4. t : The duration of time each lamp is used per day
5. BR : the kerosene burn rate (consumption rate) of each device

The product of the five factors was then multiplied by 365 days to arrive at an annual kerosene consumption rate. As described previously, these bottom-up values were then divided by the country specific residential kerosene consumption reported by IEA to arrive at an estimate of the fraction of residential kerosene used for lighting (f_{light}).

2.2.3.1.1 Factors 1-2: Households Relying on Kerosene as a Primary Lighting Fuel

Censuses or national household surveys provided the number of households (Factor 1). Factors 2-4 were taken from previous publications, nationally representative surveys performed by statistics bureaus, international survey institutions (e.g. DHS), and publicly available lighting market research. In some cases, the fraction of households relying on kerosene for lighting (Factor 2) was estimated using data on household access to electricity (see subsequent section), which is more commonly measured as part of household surveys. **Table 2.2.2** shows the list of countries used to derive regional estimates. In total, this list comprises the majority of the population in regions assumed to have non-zero lighting consumption: Central America (78%), South America (72%), African regions (73%), South Asia (72%), and Southeast Asia (71%). The kerosene lighting fraction was assumed to be zero for several regions considered most developed, including the USA, Canada, Japan, Europe and the former USSR. The same was assumed for East Asia, with the exception of China where a previous analysis of rural energy consumption found that residential oil, including kerosene, is used primarily for lighting in areas without access to grid-based electricity (*30*). One survey containing lighting information was found for the Middle East so instead estimated the fraction of kerosene lighting for the region using the data on household access to electricity in 2009, reported by IEA in 2011 (*1*).

Table 2.2.2 Percent of households using kerosene for lighting by country and region

Region	Country	Year	% Households Using Kerosene as Primary Lighting	Source
Eastern Africa	Ethiopia	2008	74%	Lighting Africa (*31*)
Eastern Africa	Kenya	2008	87%	Lighting Africa (*32*)
Eastern Africa	Madagascar*	2008	73%	DHS (*33*)
Eastern Africa	Rwanda	2002	68%	IPUMS (*34*)
Eastern Africa	Sudan	2008	40%	Ismail and Khlafala (2009) (*35*)
Eastern Africa	Uganda	2009	80%	Uganda Bureau of Statistics (*36*)
Eastern Africa	Zambia	2008	13%	Lighting Africa (*37*)
Northern Africa	Egypt*	2008	36%	DHS (*33*)
Northern Africa	Morocco*	2008	20%	DHS (*33*)
Southern Africa	Angola*	2007	55%	DHS (*33*)
Southern Africa	South Africa	2010	3%	Statistics South Africa (*38*)
Southern Africa	Swaziland*	2009	50%	CSO Swaziland (*39*)
Southern Africa	Tanzania	2008	67%	Lighting Africa (*40*)
Western Africa	Cameroon*	2004	47%	DHS (*33*)
Western Africa	Congo*	2008	75%	DHS (*33*)
Western Africa	Ghana	2007	66%	Lighting Africa (*41*)
Western Africa	Nigeria	2006	75%	NBS Nigeria (*42*)
Western Africa	Senegal	2002	19%	IPUMS (*34*)
Western Africa	Sierra Leone	2003	79%	SLIHS (*43*)
Central America	El Salvador	2007	6%	DIGESTYC (*44*)
Central America	Guatemala	2000	21%	IPUMS (*34*)
Central America	Honduras	2010	9%	INE Honduras (*45*)
Central America	Nicaragua	2005	21%	INIDE Nicaragua (*46*)
Central America	Panama	2010	8%	INE Panama (*47*)
Middle East	Jordan	2004	1%	IPUMS (*34*)
South America	Bolivia*	2008	18%	DHS (*33*)
South America	Brazil*	2009	2%	ECLAC (*48*)
South America	Colombia*	2005	3%	DANE (*49*)
South America	Jamaica	2001	9%	IPUMS (*34*)
South America	Peru*	2010	11%	INEI Peru (*50*)
South Asia	Bangladesh	2004	56%	BIDS/ESMAP (*51*)
South Asia	India	2007	34%	NSSO (*52*)
South Asia	Nepal	2001	53%	IPUMS (*34*)
South East Asia	Cambodia	2008	38%	IPUMS (*34*)
South East Asia	Indonesia	2007	5%	Statistik Indonesia (*53*)
South East Asia	Philippines	2000	27%	IPUMS (*34*)
South East Asia	Vietnam	2009	4%	IPUMS (*34*)

* Estimated from data on household access to electricity. $f_{kero} = 0.87 * f_{no\text{-}electricity} + 0.01$

2.2.3.1.2 Estimating fkero From Household Electricity Access

The percent of households using kerosene for lighting is not collected as part of all household surveys or censuses and was estimated for several countries using based on their fraction of houses without electricity. Countries used in this assessment are presented in in Table 2.2.2, surveys are representative of the year 2000 or after. **Figure 2.2.6** shows a regression of the percent of households reporting kerosene as a primary lighting fuel (f_{kero}) and the percent of households without access to electricity ($f_{no\text{-}elec}$) for 24 countries for which data were available. Information on electricity access prevalence was obtained primarily from Demographic and Health Surveys (*33*) to minimize uncertainty due to differences in the definition of electricity access. The resulting relationship between kerosene lighting and household access to electricity is approximately linear ($f_{kero} = 0.78 * f_{no\text{-}electricity} + 0.03$) with a strong correlation ($R^2 = 0.65$) that increases substantially, while altering the linear estimates very little, when one outlier (Zambia) is excluded ($f_{kero} = 0.87 * f_{no\text{-}electricity} + 0.01$, $R^2 = 0.79$; applied in **Table 2.2.2**). Zambia is unique among other countries represented in the dataset, as the majority of households are without electricity (82%), however lighting is performed almost entirely with candles (*37*). Overall, these results provide supporting evidence that kerosene is still the primary source of household lighting fuel in areas without access to electricity.

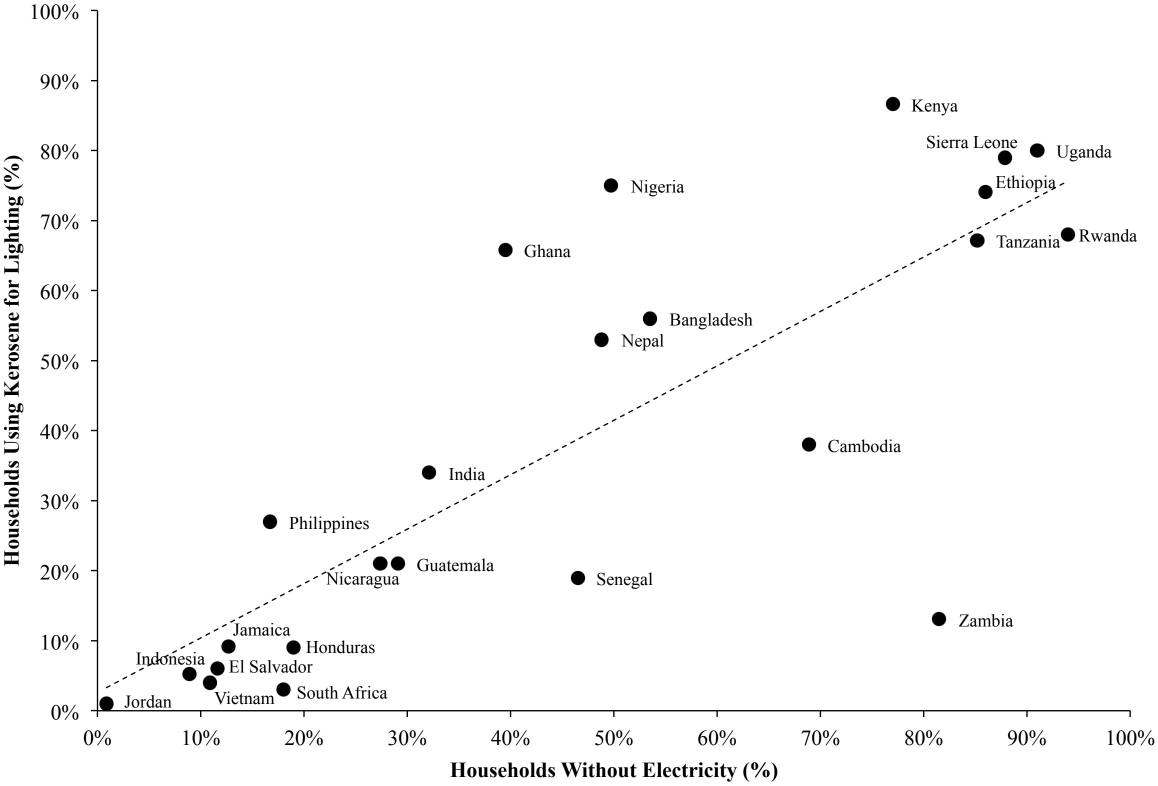


Figure 2.2.6. Percent of households reporting kerosene as a primary source of lighting (f_{kero}) versus the percent of households without access to electricity ($f_{no\text{-}elec}$) (N = 24). The

dashed line represents the best-fit line using all available data (All Data, $R^2 = 0.65$; without Zambia, $R^2 = 0.79$)

2.2.3.1.3 Factors 3-5: Lamp numbers, time of use per day and burn rates

The number of lamps used in the house (Factor 3) was estimated at 2 per house and a triangular distribution bounded at (1, 3), with the exception of Africa where several detailed surveys were available (see subsequent section on regional estimates). Use was estimated at 3 hours per day with a triangular distribution bounded at (2, 4). The selection of a fuel burn rate (Factor 5) was guided by measurements reported in this study, with a central value of 0.12 g/min and 90% uncertainty bounds (0.05, 0.20) and a normal distribution.

The burn rate from simple wick lamps is applied to all kerosene lighting devices, including hurricane lamps, so the estimate of kerosene consumption for lighting is likely conservative as simple wick lamps have the lowest burn rate of the lighting devices commonly used in households (*18*).

2.2.3.2 Regional Level Estimates

2.2.3.2.1 South Asia (Excluding India)

Kerosene lighting is prevalent in several South Asian countries outside of India. Household lighting information for Bangladesh (~5% South Asian population) was available from rural energy surveys collected by the Bangladesh Institute of Development Studies in 2004, and summarized recently by the Energy Management Assistance Program (*51*). These surveys indicate that approximately 71% of rural households rely on kerosene devices (simple wick or hurricane) as primary lighting sources (average 1.8 simple wicks, and 0.89 hurricanes per house). Assuming the urban sector has minimal usage of kerosene for lighting and considering the urban/rural population fraction provided in the same report (~80% rural), 71% of rural households corresponds to approximately 56% of all households. Results from the 2001 census in Nepal indicate that 53% of households relied on kerosene fuel as a primary lighting source (*34*), however this number may be different now, given the age of the dataset.

2.2.3.2.2 India

Results from the National Sample Survey Organization 61st round were used to inform estimates of kerosene use for lighting in India (*52, 54*). Kerosene consumption for lighting was estimated for each state using survey results on state-level fractions of households using kerosene lighting as primary sources of lighting and number of households (mean household size of 5 persons). Lamp usage assumptions, central estimates and uncertainty bounds, were 2 (1, 4) kerosene lamps per household, 4 (3, 5) hours of use per day (*55*), and a burn rate guided by results from this study of 0.12 g/min (0.05, 0.20), and the same distributions discussed previously. The prevalence of kerosene devices are not collected as part of NSSO surveys, however, several sources indicate that simple wicks are the dominant device used in households without access to electricity (*56, 57*). As with all global estimates, these estimates do not consider the use of lighting for small-scale businesses (e.g. retail stalls, fishing).

In India, household kerosene use is typically limited to cooking and lighting (no heating). NSSO surveys also provide information on cooking fuels used in households. Based on household consumption surveys reported by NSSO, rural use of kerosene for lighting reduced from 103 to 72 households per thousand, between 2000 and 2005 (*52*). There was no reduction, however, in per capita rural kerosene use in the same period (*52*). This implies that larger amounts of kerosene use for lighting and cooking may occur, with kerosene replacing electricity for lighting and fuel wood for cooking. The use of kerosene as a secondary cooking fuel is common, but secondary uses are not measured as part of NSSO assessments and therefore not included in the fraction of households reported as cooking with kerosene. Daily electricity outages (or load shedding), especially during the evening peak-load period, occur for 2.5-4 hrs and 11-12 hrs in urban and rural consumer segments, respectively (*58*). Assuming a central frequency at which kerosene substitutes for electric lighting of 25% (rural) and 10% (urban), adds to the fraction of households using kerosene lighting. The average household in India requires 11 MJ of delivered energy for daily cooking requirements (*59*), which can be converted to an equivalent kerosene consumption rate using the energy density of kerosene (42.6 MJ/kg kerosene) and the average efficiency of the kerosene cooking stove (*25, 59*).

2.2.3.2.3 African Regions

National household survey data confirm anecdotal accounts of kerosene fuel being a primary and dominant source of lighting fuel in African households. In East Africa several in-depth and nationally representative evaluations of household lighting by Lighting Africa, and statistics bureaus (e.g. Uganda and Rwanda) have been performed. Several sources provide data on the number of lighting devices used per house, estimated hours of daily usage, and the prevalence of lighting devices (e.g. simple wick, hurricane, electric bulb, candles etc.). Based on these sources a central estimate of 1.3 simple wick lamps per household is used. Usage hours and burn rate were the same as those used for all other regions and described previously. Data from the following countries was used in this analysis (**Table 2.2.3**):

Table 2.2.3 Sources for African continent estimates by region

Region	Countries
Eastern Africa	Ethiopia 2007/2008 (*60*), Kenya 2007/2008 (*32*), Zambia 2007/2008 (*61*)
Northern Africa	Sudan 2008 (*35*), Egypt 2006 [a] (*34*), Morocco 2003 [a] (*33*)
Western Africa	Ghana 2007/2008 (*41*), Nigeria 2006 (*42*)
Southern Africa	South Africa 2010 (*38*), Tanzania 2007/2008 (*40*)

[a] had much greater fuel use relative to Sudan

While some information from other countries was available (Uganda, Madagascar, Sierra Leone, Rwanda, Senegal), it was not used to develop estimates of f_{light} because IEA does not report disaggregated fuel statistics for these countries.

Several surveys (e.g. Lighting Africa Market Reports, Ugandan Household Survey, Sudanese Census) provide detailed information on the primary type of lighting device used (*36*). A population-weighted average for all reporting countries indicates that 62% of kerosene lighting devices used in houses are of the simple wick type, while the remainder is primarily hurricane wick lamps.

2.2.3.3 Outdoor Escape Fraction (foutdoor)

Calculation of emissions (*EM* in Equation 1) includes the fraction of the emissions that escapes outdoors ($f_{outdoor}$). No estimates of indoor to outdoor escape fractions in the literature were found, but several studies have sought to characterize the penetration of outdoor particles to indoors. Emissions can be either deposited indoors, or they may be carried in indoor air transported to outdoors. During the latter journey, the emissions may deposit within the crack that leads to outdoors. However, Liu and Nazaroff (*62*) found a near-unity penetration rate for particles of sizes similar to those emitted from combustion; that is, crack deposition is negligible. Thus, this loss mechanism is ignored. Indoor deposition rates reported in outdoor-to-indoor modeling are 0.12 h^{-1} with uncertainty bounds of 0.09 to 0.33 h^{-1} for residential buildings (*63*). Combined with estimates of air-change rates for buildings without insulation (1 h^{-1} with uncertainty bounds of 0.5-3 h^{-1}), a mass balance gives an outdoor escape fraction of 0.89 (triangular distribution bounded at 0.78, 1).

2.2.4 Uncertainty Propagation

Uncertainties for final emission estimates were calculated using Monte Carlo simulation. This method relies on random sampling from set of parameters of given distribution, which are then combined following a known function. Probability distributions for each parameter are known or estimated based on empirical evidence (e.g. sample distributions), or are assumed based on a-priori assumptions. The function is evaluated several thousand times and the results from each iteration stored. Confidence intervals, therefore, can be empirically calculated by ranking the results and are therefore not dependent on assumptions of functional. In this case, Monte Carlo was used to calculate uncertainty for emission estimates which are a function of several parameters defined in previous sections, including the pollutant emission factor, lighting device fractions, outdoor escape fraction, hours of operation per day and days of use per year. Because of the flexibility of Monte Carlo, it is used in a wide range of applications and disciplines and implemented in many software packages. Simulations here were performed in Matlab and Crystal Ball, an add-in to Microsoft Excel.

2.3 Results & Discussion

2.3.1 Emission Factors

The average EF_{PM} for a simple wick lamp operated at baseline settings in laboratory tests was 81 ± 15 g/kg kerosene, while device-specific EF_{PM} ranged from 71-87 g/kg kerosene; in other words, 7-9% of the fuel is converted to particulate matter (**Table 2.3.1, Figure 2.3.1a-c**). The majority of PM mass was BC, with measured BC/TC ratios ranging from 0.88-1.00 and an EF_{BC} of 76 ± 15 g/kg kerosene. Variation in EF_{BC} was 9-23% for tests of a single lamp and about 20% for similar tests on different lamps. EF_{OC} ranged from 4-6 g/kg kerosene, so the ratio between OC and BC was 0.06 ± 0.05 (**Table 2.3.2**). EF_{BC} from a hurricane lamp was 9 ± 1 g/kg kerosene, or 8-10 times lower than the average simple wick device, but the majority of PM mass was still BC (BC/TC = 0.95 ± 0.03). EF_{CO} for the simple wick and hurricane lamps were 16 ± 1 g/kg kerosene and 3 ± 1 g/kg kerosene, respectively.

EF_{PM} measured in the lab for a hurricane lamp (13 g/kg) is consistent with the EF_{PM} reported by Fan and Zhang (*17*) for a hurricane lamp operated at high wick setting (EF_{PM} = 9.0 ± 4.0 g/kg), and four times higher than their emission at a normal flame height (EF_{PM} = 3.3 ± 2.8 g/kg). Higher EF_{BC} values have been measured when hurricane lamps generated soot for research purposes (*19, 20*), but these conditions would cause the lamp glass to quickly cover in soot, reducing useful light.

2.3.1.1 Sensitivity of Emission Factors to Operating Conditions

Heightening the wick of a simple lamp to increase illumination is common in households. At high wick settings, the fuel burn rate increased, and the average EF_{BC} increased by 28 g/kg (38%), with a smaller 5 g/kg (30%) increase in average CO and no change in EF_{OC}. Since sensitivity was only conducted on a single lamp, comparisons are made against the same lamp under standard conditions as opposed to the average performance of a simple wick lamp.

Several other modifications to baseline lamp settings could alter emissions. The simple wick of a liquid-fuel lamp is fashioned from cloth or rope. Fuel is transported by capillary action and the rate of transport might be influenced by material. When rope was used in place of cloth, no significant difference in emissions or fuel burn rate was observed. Burning Ugandan kerosene in place of fuel produced in the United States (1-K) increased average EF_{PM} by 42%, but had no significant effect on EF_{BC}, EF_{OC}, or EF_{CO}. The greater PM from imported Ugandan fuel might be explained by its approximately doubled sulfur content (0.08 Wt%), or 13% increase in aromatic content (18 Vol%), based on fuel analysis.

Table 2.3.1. Laboratory and field-based emission factors and burn rates for simple wick and hurricane lamps

		Sample		**Emission Factors**					**Burn Rate**
				g/ kg fuel					*g fuel/hour*
		Device ID	n	**BC**	**OC**	**$PM_{2.5}$**†	**CO**	**CO_2**	
Lab	Low Wick	**Avg.**	**9**	**76 (15)**	**5 (4)**	**81 (15)**	**16 (1)**	**2800 (60)**	**6 (2)****
Simple Wick		1	3	66 (16)	6 (2)	71 (7)	16 (1)	2820 (60)	5 (1)
		2	3	89 (8)	4 (0.1)	87 (18)	18 (1)	2750 (30)	8 (0.6)
		3	3	72 (9)	4 (6)	85 (14)	16 (1)	2810 (50)	5 (0.2)*
	High Wick	3	3	110 (4)	3 (3)	95 (12)	21 (1)	2700 (5)	12 (0.4)
	Rope Wick	3	3	79 (6)	3 (4)	70 (8)	16 (1)	2790 (10)	=6 (0.3)
	Ugandan Kerosene	2	3	91 (2)	2 (1)	124 (7)	16 (1)	2750 (8)	7 (0.2)
Field	Typical	**Avg.**	**7**	**90 (17)**	**0.4 (0.8)**	**93 (23)**	**11(2)**	**2770 (70)**	**7 (2)****
Simple Wick		4	4	94 (19)	1 (1)	100 (19)	12 (2)	2750 (73)	9 (3)*
		5	1	89 (-)	< 1 (-)	4 (-)	11 (-)	2770 (-)	6 (-)
		6	2	76 (-)	4 (-)	79 (-)	8 (-)	2800 (-)	6 (-)
Lab *Hurricane*	Med/High Wick	7	3	9 (1)	0.5 (0.3)	13 (3)	3 (<1)	3080 (5)	26 (1)

Numbers in parentheses represent one standard deviation

n = measurement events, * n = 2 (lab); n = 3 (field), ** n = 8 (lab); n = 6 (field) due to missing data

Baseline settings are low wick (1-1.5mm), 1-K USA kerosene, and cotton cloth wick, unless specified otherwise

† Field results represent total suspended particles (TSP)

Table 2.3.2. Laboratory and field-based emission ratios and aerosol optical properties for simple wick and hurricane lamps

		Sample		**Ratios**				**Optical Properties**‡		
								m^2/g	*m^2/g*	
		Device ID	n	**BC/ $PM_{2.5}$**†	**BC/TC**	**OC/TC**	**OC/BC**	**MAC_{BC}**	**MSC_{PM}**	**SSA**
Lab	Low Wick	**Avg.**	**9**	**0.95 (0.23)**	**0.95 (0.05)**	**0.06 (0.05)**	**0.06 (0.05)**	**7.0 (0.6)**	**2.5 (0.5)**	**0.27 (0.01)**
Simple Wick		1	3	0.94 (0.18)	0.91 (0.01)	0.09 (0.03)	0.09 (0.02)	7.0 (0.8)	2.2 (0.4)	0.26 (0.01)
		2	3	1.06 (0.31)	0.96 (<0.01)	0.04 (0.01)	0.04 (<0.01)	7.2 (0.7)	2.9 (0.6)	0.28 (<0.01)
		3	3	0.86 (0.08)	0.96 (0.07)	0.04 (0.07)	0.05 (0.08)	6.8 (0.2)	2.2 (0.1)	0.28 (0.01)
	High Wick	3	3	1.07 (0.15)	0.97 (0.03)	0.03 (0.03)	0.03 (0.03)	7.1 (0.1)	3.1 (0.4)	0.29 (<0.01)
	Rope Wick	3	3	1.15 (0.21)	0.97 (0.04)	0.04 (0.05)	0.03 (0.05)	7.0 (0.2)	3.0 (0.5)	0.27 (<0.01)
	Ugandan Kerosene	2	3	0.73 (0.04)	0.98 (0.01)	0.02 (0.01)	0.02 (0.01)	7.1 (0.2)	2.1 (0.1)	0.29 (<0.01)
Field	Typical	**Avg.**	**7**	**1.02 (0.3)**	**1.0 (0.01)**	**<0.01 (0.01)**	**< 0.01 (< 0.01)**	**11.1 (1.6)**	**1.9 (0.6)**	**0.17 (0.01)**
Simple Wick		4	4	0.9 (0.1)	1.0 (<0.01)	<0.01 (<0.01)	< 0.01 (<0.01)	10.7 (1.2)	1.8 (0.4)	0.17 (-)
		5	1	1.0 (-)	0.98 (-)	0.02 (-)	0.02 (-)	10.3 (-)	1.8 (-)	0.16 (-)
		6	2	1.4 (0)	1.0 (-)	<0.01 (-)	< 0.01 (-)	11.5 (-)	3.1 (-)	0.17 (-)
Lab *Hurricane*	Med/High Wick	7	3	0.66 (0.05)	0.95 (0.03)	0.05 (0.03)	0.06 (0.04)	6.5 (0.1)	1.1 (0.1)	0.20 (0.00)

Numbers in parentheses represent one standard deviation

Baseline settings are low wick (1-1.5mm), 1-K USA kerosene, and cotton cloth wick, unless specified otherwise

† Field results represent total suspended particles (TSP)

‡ MAC – mass absorbance cross section (530 nm), MSC – mass scattering cross section, SSA – single scattering albedo

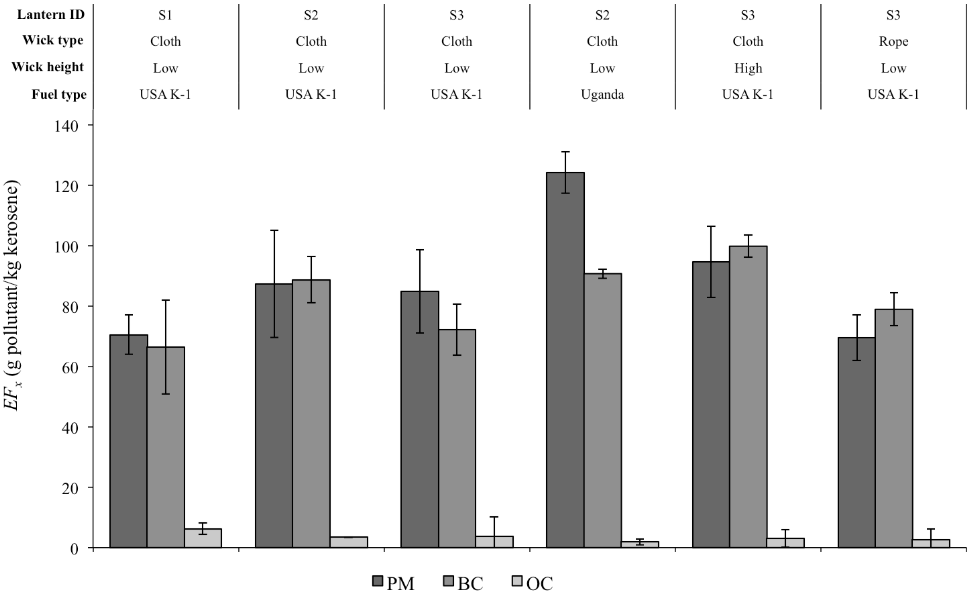


Fig. 2.3.1a. Average $PM_{2.5}$, BC and OC emission factors from simple wick lamps tested under lab conditions. Errors bars represent ± 1 standard deviation of repeated tests.

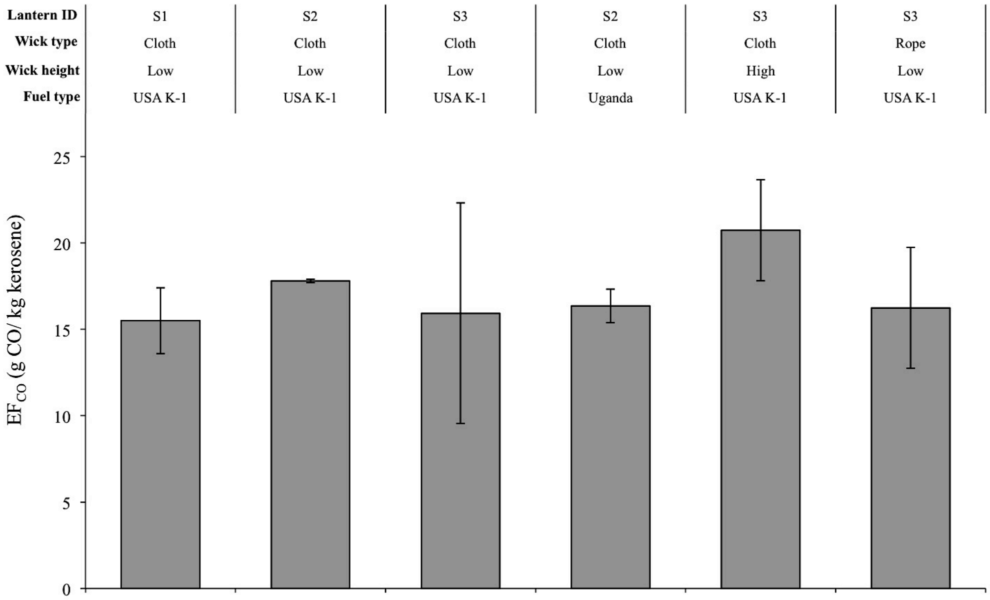


Fig. 2.3.1b. Average CO emission factors from simple wick lamps tested under lab conditions. Errors bars represent ± 1 standard deviation.

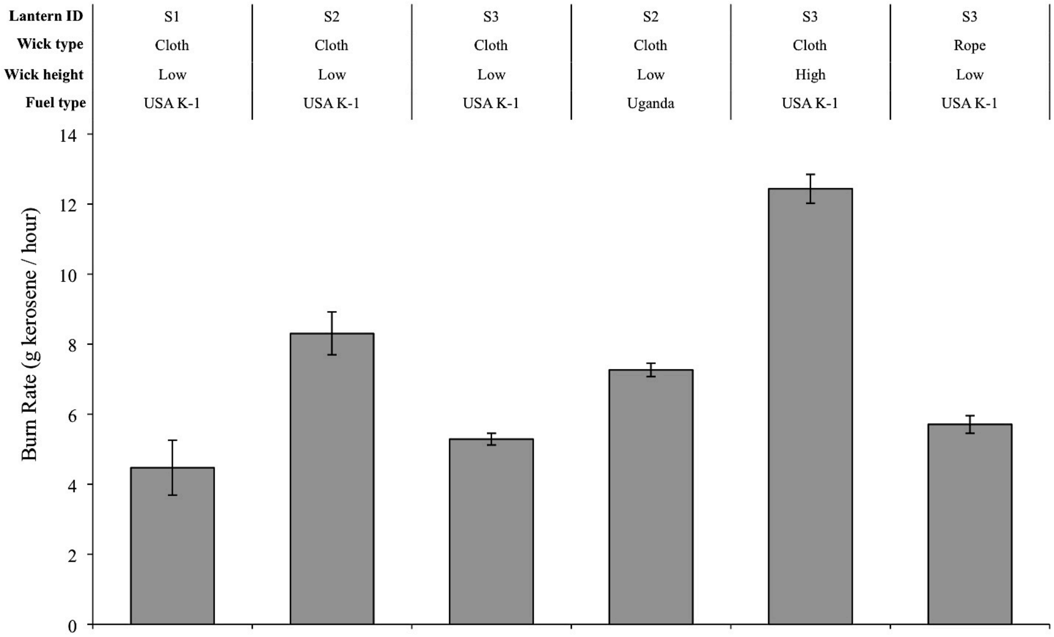


Fig. 2.3.1c. Burn rates from simple wick lamps tested under lab conditions. Error bars represent ± 1 standard deviation.

2.3.1.1.1 Real-time Pollutant Concentrations

Real-time concentrations over one test are shown here to demonstrate the relative stability of kerosene lamp emissions during burning (**Figures 2.3.2a-c**), in contrast with the highly fluctuating nature of biomass cookstove emissions (for an example of typical fluctuations in PM emissions see **Figure A3.3**).

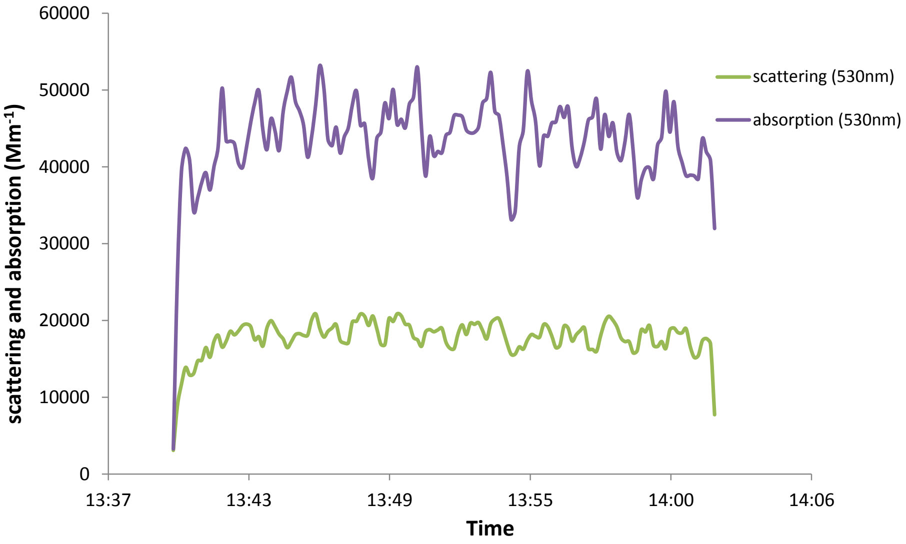


Fig. 2.3.2a. Real-time concentrations for particle optical properties over a single test (scattering and absorption). Data are averaged every ten seconds.

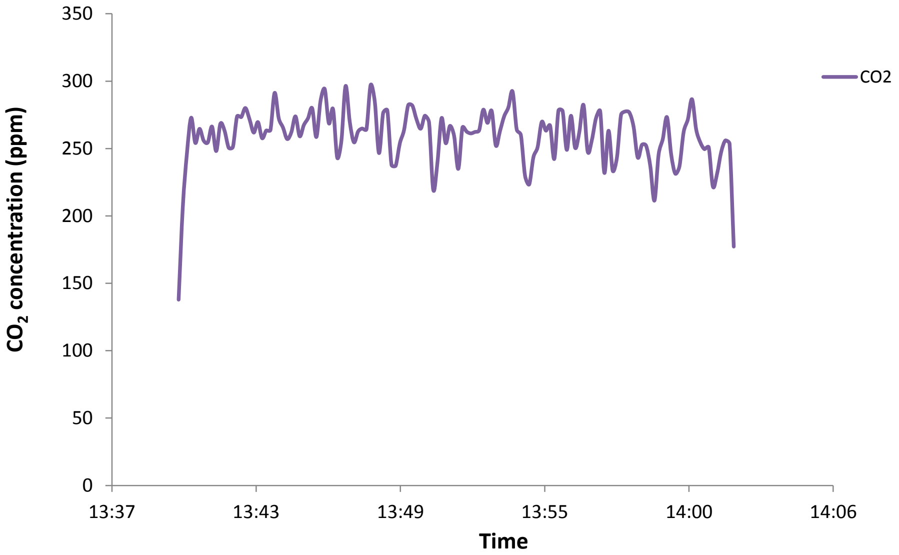


Fig. 2.3.2b. Real-time concentrations of CO_2 over a single test. Data are averaged every ten seconds.

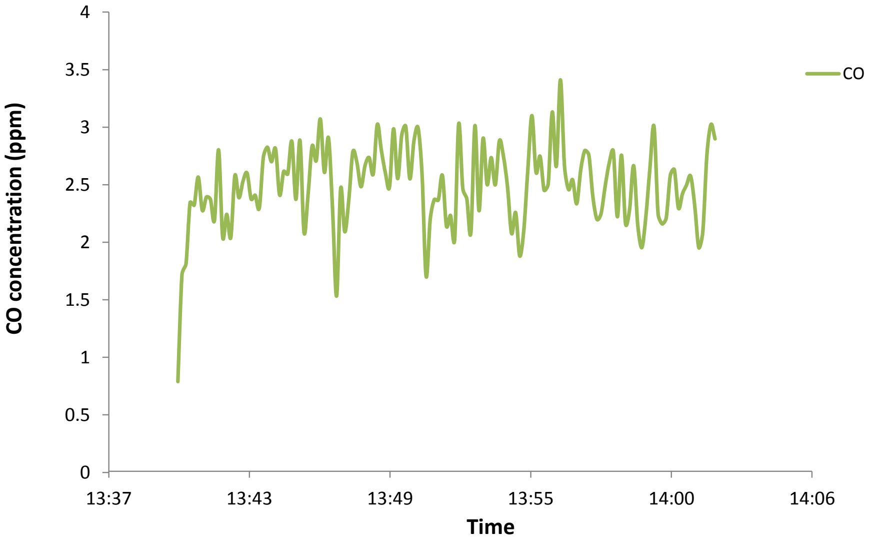


Fig. 2.3.2c. Real-time concentrations of CO over a single test. Data are averaged every ten seconds.

2.3.1.2 2.3.1.2 Emission Factor Variability

Much of the variability in EF_{BC} is associated with variation in the rate of kerosene consumption ("burn rate" or X_{BR}). **Figure 2.3.3** summarizes all field measurements and sensitivity tests, showing that EF_{BC} and X_{BR} have an approximately linear relationship

($EF_{BC} = 240X_{BR} + 54$, $R^2 = 0.52$). This relationship changes by less than 2% after adjusting for unbalanced repeated measurements by aggregating by lamp or applying mixed effects models. Combining this relationship with the central value of fuel burn rate (0.12 g min^{-1}) gives an EF_{BC} for a simple wick lamp of 83 g/kg kerosene, with 90% uncertainty bounds of (63, 109). The average values of EF_{BC} and EF_{PM} collected in Western Uganda from simple wick lamps were higher than those measured under laboratory conditions by 14 g/kg kerosene (18%) and 12 g/kg kerosene (12%), respectively. Much of the discrepancy between laboratory and field-based emissions can be explained by differences in fuel burn rates.

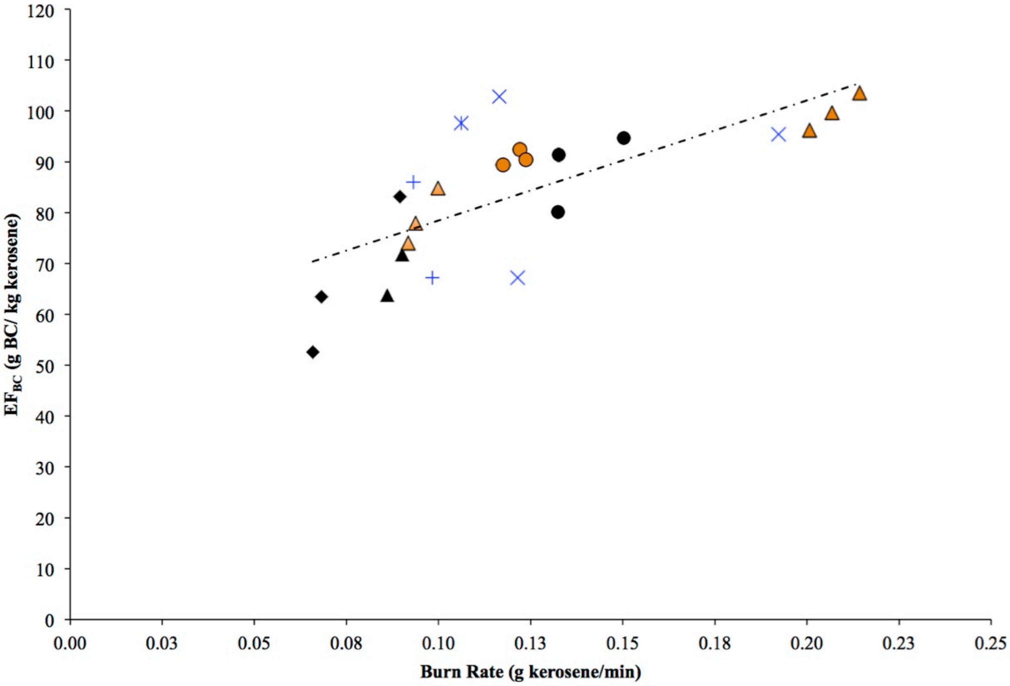


Figure 2.3.3. EF_{BC} versus kerosene burn rate from laboratory (black and orange) and field (blue) emission measurements. Marker shapes represent individual simple wick devices. Black markers represent simple wick lamps operated at baseline conditions. Orange markers represent altered lamp settings: high wick (triangles on far right of figure), rope wick (triangles on left), and Ugandan kerosene (circles). The dotted line is the line of best fit ($R^2 = 0.52$).

2.3.1.3 BC Emission Factors Relative to Other Major Source

The average EF_{BC} for a simple wick lamp of 76 ± 15 g/kg kerosene, and the BC/TC ratio of 0.95 ± 0.05, are much higher than other sources of BC (**Figure 2.3.4**) (*64*). In contrast, EF_{CO} (not shown in figures) was lower than that from other BC sources at 16 ± 1 g/kg. BC emission factors from simple wick lamps are two orders of magnitude higher than those from kerosene-fueled cookstoves. Cooking uses the heat produced when fuel is converted to carbon dioxide and water, and it is most efficient when combustion is complete. In contrast, BC within a flame is the agent of illumination, and simple lighting devices therefore must produce BC. Then, rapid cooling of combustion effluents prevents further oxidation, resulting in high BC emissions.

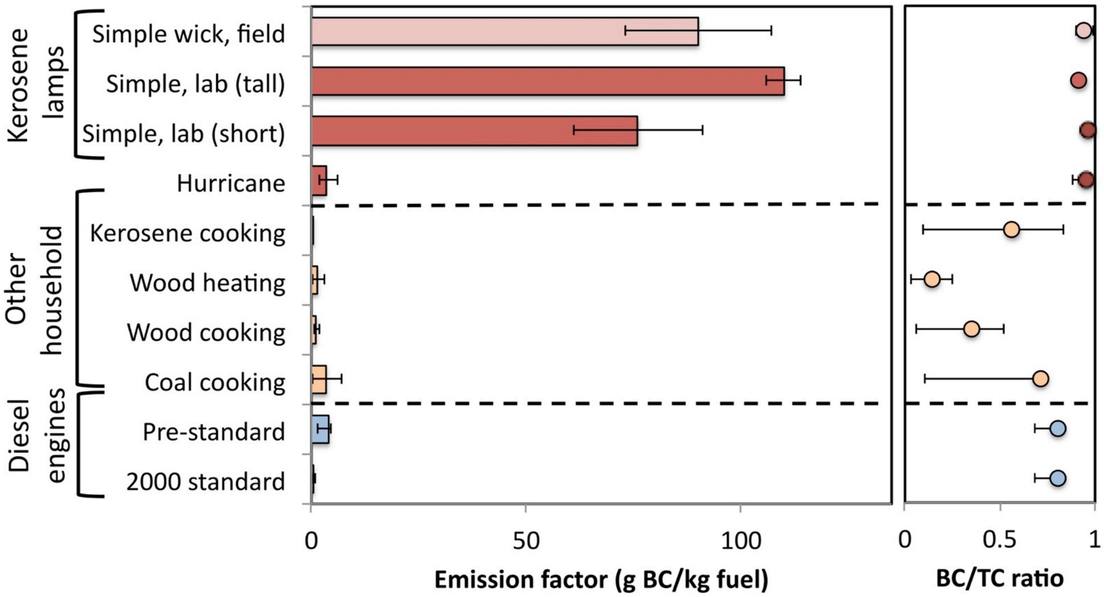


Figure 2.3.4. Comparison of emission factors for black carbon (EF_{BC}) and black carbon fraction of total aerosol carbon (BC/TC) for kerosene lamps, other household uses, and diesel engines. Error bars represent 90% uncertainty bounds. Non-lighting emission factors are taken from Bond (2004) (*64*)

2.3.2 Aerosol optical properties

Three climate relevant characteristics of aerosols are single-scattering albedo (SSA), which is the fraction of extinction caused by scattering rather than absorption; mass absorption cross-section (MAC_{BC}), which is the absorption cross-section per BC mass; and the mass scattering cross-section (MSC), which is the scattering cross-section per PM mass. Particles from lamps had SSA of 0.25-0.30, mass scattering cross-section of 1.9-3.1 m^2/g, and mass absorption cross-section of 6.4-7.8 m^2/g (530 nm) (Table 1). These values are similar to those of freshly generated, pure BC particles (SSA = 0.2–0.3; MAC = 7.5 ± 1.2 m^2/g at 550 nm) (*65*). Therefore, particles emitted from simple wick lamps have both the chemical and optical properties of nearly pure BC.

2.3.3 Global kerosene consumption for lighting

In the year 2005, residential use of kerosene fuel was only 0.5% of global energy consumption (*28, 29*). The most recent emission inventories, lacking measured values for BC and OC emitted from lighting, used emission factors from cooking stoves for all uses of kerosene (*64, 66*). Because the two emission factors are so different, improving emission inventories first requires an estimate of the amount of kerosene used for lighting.

As discussed in the methods section, the fraction of kerosene used for lighting was estimated based on analysis of survey data. Combining available information on kerosene lighting prevalence and usage patterns led to an estimate of global kerosene consumption for residential lighting of 5,000 Gg/year, with 53% attributable to simple wick lamps. This constitutes 25% of the reported residential kerosene consumption in South Asia and 29% in African countries. These estimates are restricted to household consumption and do not consider usage in other sectors (e.g. public or small scale business lighting).

Consumption estimates in India, one of the largest consumers of residential kerosene, were further constrained using information from a large consumer expenditure survey on the household consumption of goods and services. This survey, conducted by the National Sample Survey Organization (NSSO), includes per-capita kerosene consumption for combined lighting and cooking and reports values separately for the rural and urban population in each state (*52, 54*). Using NSSO survey results and the number households in each state, but applying separate consumption rates for lighting and cooking, led to estimates of consumption for lighting of 2500 Gg/year for 2005. The central estimate for kerosene cooking was 6700 Gg/year for 2005. For comparison, the estimate of combined consumption of 9200 Gg, is in agreement with that estimated from reported per-capita consumption data given by NSSO surveys (8550 Gg), and the value reported by IEA (9377 Gg) for total residential applications. Thus, lighting accounts for approximately one quarter of the annually reported residential kerosene consumption in India, while cooking, which consumes fuel at a significantly faster rate (*25, 59*), and diversion of government subsidized kerosene to non-residential sectors may account for the remainder.

2.3.4 BC emission rates

Emission factors for simple wick lamps were based on the central estimate of fuel burn rate, as stated previously. A value of EF_{BC} for hurricane lamps was estimated as 2.2 g BC/kg kerosene (1.3, 5.0) using EF_{PM} values reported by Fan and Zhang (*17*) along with the BC/TC ratio measured in this study for a hurricane lamp (0.95 ± 0.03).

Applying these emission factors to fuel consumption estimates, the central value of atmospheric emission rate from residential kerosene lighting is 270 Gg BC/year. A Monte Carlo analysis considering uncertainties in the parameters gives (110, 590) Gg BC/year as 90% uncertainty bounds (See 2.2.3.4 for a description of Monte Carlo methods) .

Table 2.3.3 presents assumptions and BC emission for 19 regions that were based on the 17 regions used in a common macroeconomic model (Integrated Model to Assess the Global Environmental or IMAGE, RIVM, 2001). The two additional regions, China and India, were separated from East Asia and South Asia, respectively. Country groupings in these regions may be slightly different than other common aggregations such as those used by the United Nations. **Figure 2.3.5** shows the results of a 10,000-run Monte Carol simulation. Uncertainties determined with the Monte Carlo simulation, which are used in the text, differ slightly from the simple combination of uncertainties shown in **Table 2.3.3**.

Previous estimates that assumed only cooking emission factors for residential kerosene use resulted in negligible estimates of emissions: 12 Gg BC and 34 Gg OC per year for all kerosene uses. For comparison with other BC sources, a total of 1320 Gg BC and 280 Gg OC are estimated from diesel engines, or 1900 Gg BC and 7700 Gg OC from cooking and heating with solid fuels (biomass and coal) (*64*). The estimated BC emissions from lamps alone are 20-25% of the global BC emissions from diesel engines and 10-15% of BC from residential use of solid fuel (*64*). While BC emissions from kerosene lamps are smaller in absolute terms than other major source categories, their contribution is notable because the quantity of fuel consumed is much lower, and because their contribution to BC emissions has previously been assumed to be negligible.

Table 2.3.3. Assumptions for 17 global regions. Values in parentheses for f_{light} and f_{device} are the bounds of a triangular distribution. Values in parentheses for emissions show lower and upper estimate bounds with a simple uncertainty combination; these are not the same as those obtained with the Monte Carlo.

	Fraction of residential kerosene used for lighting (f_{light})	**Fraction of kerosene used by simple wick lamps (f_{device})**	**Black carbon emissions[a] (EM_{BC})**
			Gg/year
Canada	0 (0, 0)	0 (0, 0)	0 (0, 0)
USA	0 (0, 0)	0 (0, 0)	0 (0, 0)
Central America	0.277 (0.029, 0.866)	0.5 (0, 0.7)	13 (0, 41)
South America	0.256 (0.023, 0.8)	0.5 (0, 0.7)	3 (0, 10)
Northern Africa	0.615 (0.099, 1)	0.6 (0.3, 0.9)	19 (0, 35)
Western Africa	0.245 (0.039, 1)	0.6 (0.3, 0.9)	32 (0, 132)
Eastern Africa	0.526 (0.084, 1)	0.6 (0.1, 0.9)	12 (0, 25)
Southern Africa	0.01 (0.001, 0.05)	0.6 (0.3, 0.9)	0 (0, 0)
OECD Europe	0 (0, 0)	0 (0, 0)	0 (0, 0)
Eastern Europe	0 (0, 0)	0 (0, 0)	0 (0, 0)
Former USSR	0 (0, 0)	0 (0, 0)	0 (0, 0)
Middle East	0.006 (0.001, 0.02)	0.25 (0.1, 0.5)	1 (0, 4)
South Asia (excl. India)	0.521 (0.054, 1)	0.8 (0.7, 0.95)	40 (3, 79)
India	0.21 (0.05, 0.52)	0.8 (0.7, 0.95)	116 (23, 291)
East Asia (excl. China)	0 (0, 0)	0 (0, 0.4)	0 (0, 0)
China	0.8 (0.5, 1)	0.8 (0.25, 0.95)	13 (4, 18)
Southeast Asia	0.026 (0.003, 0.08)	0.8 (0.5, 0.8)	14 (0, 43)
Oceania	0 (0, 0)	0 (0, 0)	0 (0, 0)
Japan	0 (0, 0)	0 (0, 0)	0 (0, 0)
Total			**263 (30, 678)**

a - Totals, especially uncertainty bounds, are different from those reported in the main text because this is a simple combination of uncertainties, while the text reports results of Monte Carlo simulations.

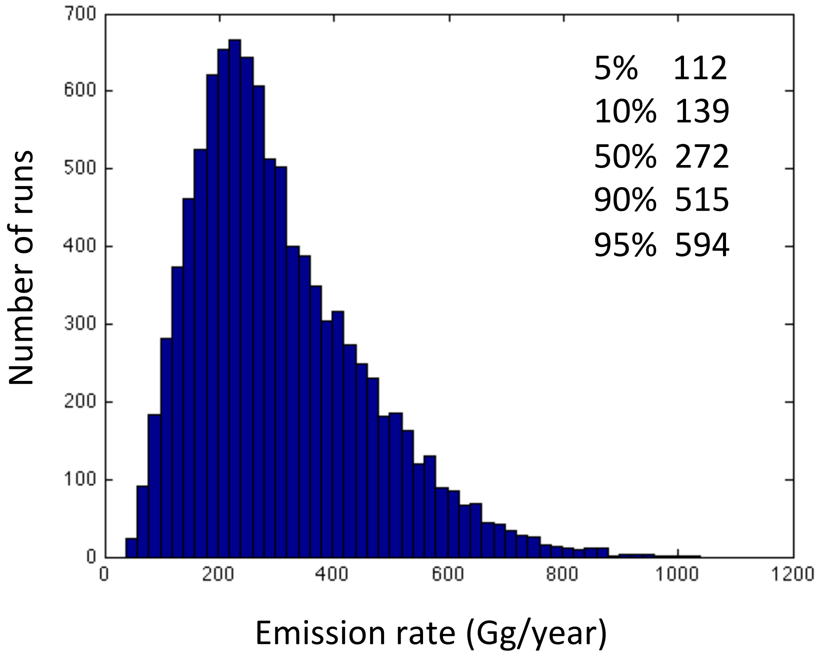


Figure 2.3.5. Frequency distribution and percentiles of the global BC emission rate based on a Monte Carlo simulation of 10,000 runs.

2.3.4.1 Comparison to Other Emission Estimates

Emissions of BC were estimated using a separate and independent assessment of the demand for kerosene from fuel-based lighting performed in 2102 by the UN Enlighten Initiative. As part of the assessment, kerosene consumption for lighting was estimated for 62 countries, including 34 in Africa, 14 in Asia, 5 in North America, 2 in Latin America and 1 in Europe. Also provided are estimates of lighting stock - simple wick and hurricane – based on existing surveys or extrapolated from countries (details not described in detail).

Annual Kerosene consumption for lighting was estimated at 25 billion liters, or 21,000 Gg, approximately 4 times greater than estimates obtained in this assessment. The greater demand was largely attributed to assumed higher burn rates for kerosene lamps, which were 30-60% higher than burn rates used here. Furthermore, the group considered differences between the burn rate of simple wick lamps and the more energy intensive hurricane lamps, while our evaluation applied a universal burn rate equivalent to the simple wick lamp. As with this evaluation, the study primarily considered households without electricity. Resulting BC emissions based on device-specific fuel consumption were 550 Gg BC, approximately 50% higher than estimates here. **Table 2.3.4a** shows estimated emissions from UN En.Lighten using the same global regions applied in this study (**Table 2.3.3)**. Unlike this study, the authors have not extrapolated to the region based on existing data, thus values presented are the sum of countries evaluated within the specified region.

Table 2.3.4a. BC emissions based on consumption and device stock estimates from the UN En.Lighten Initiative. Regional emission total represent the sum of individual emissions of all countries evaluated ("country count") and are not an extrapolation to the entire region as they are in **Table 2.3.3**

Region	**Countries Representing**	**BC Emissions (Total)**
		GgBC/yr
Canada[1]	NR	**0**
USA[1]	NR	**0**
Central America	5	**8**
South America	3	**3**
Northern Africa	0	**0**
Western Africa	18	**136**
Eastern Africa	9	**141**
Southern Africa	10	**47**
OECD Europe[1]	NR	**0**
Eastern Europe[1]	NR	**0**
Former USSR	1	**1**
Middle East	2	**7**
South Asia (excl. India)	4	**25**
India	1	**129**
East Asia (excl. China)	2	**8**
China	1	**4**
Southeast Asia	6	**67**
Oceania[1]	NR	**0**
Japan[1]	NR	**0**
	Total	**576**

[1] Countries assumed to have zero emissions but shown for completeness and for comparison to **Table 2.3.3**

NR = Not represented but assumed zero given level of development

Table 2.3.4b. Countries included as part of En.Lighten Assessment for calculations in Table 2.3.4a by IMAGE regions.

Country/Region	Countries
Central America	El Salvador, Guatemala, Haiti, Honduras, Mexico
China	China
East Asia	Korea, Mongolia
Eastern Africa	Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Somalia, Sudan, Uganda
Former USSR	Ukraine
India	India
Middle East	Iraq, Yemen
South America	Brazil, Bolivai, Guyana
South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka
Southeastern Asia	Cambodia, Indonesia, Laos, Myanmar, Timo Leste, Viet Nam
Southern Africa	Anglola, Botswana, Lesotho, Malawi, Mozambique, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe
Western Africa	Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Cote D'Ivoire, DRC, Equitorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea Bisseau, Liberia, Mauritania, Nigeria, Rep of Congo, Togo

2.3.5 Contribution to Black Carbon Inventories

Modeled atmospheric concentrations based on current emission inventories, which do not include kerosene-based lighting sources, predict absorbing aerosols reasonably well in most world regions, with South Asian and African regions being exceptions (*67*). Surface (*68*) and aircraft (*69*) measurements report unexpectedly high concentrations of BC in South Asia, where particles are much more absorbent than in other world regions (*70*). These observations are consistent with large unquantified sources of very dark aerosol that may be explained, at least in part, by the use of kerosene lighting in both regions. This "missing" source of black carbon may explain why estimates of aerosol impacts indicate much greater atmospheric absorption in Asia when observational constraints using satellite imaging are applied (*71*).

Caution is warranted in comparing the effects of short-lived climate forcing agents with those of long-lived greenhouse gases. Nevertheless, dividing the energy added to the Earth system by short-lived climate forcers by the integrated forcing of CO_2 yields an approximate estimate of equivalence (*6*). The direct forcing (not considering effects of albedo change on snow) by one year's BC and OC emissions from kerosene lamps is equivalent to the forcing that 230 Tg (Mtonne) of CO_2 exerts over 100 years after emission. This emission level is equivalent to about four percent of the United States' CO_2 emissions in 2008.

2.3.6 Implications for Mitigation of Short-Lived Climate Forcers

Reductions in emissions of BC and other short-lived climate forcers have been proposed to play an important role in limiting temperature increases over the next 50 years (*10*). The previous lack of information about kerosene lighting emissions, however, means that this BC source has been excluded from such discussions. Replacements for kerosene lighting do exist. Providing reliable and affordable electricity to households is an ideal alternative, but other options are available while the required infrastructure is built. For example, low cost light-emitting diode lamps are now designed for developing-country markets, charged by photovoltaic cells or electricity during non-peak hours. Even kerosene-fueled hurricane lamps or pressurized mantle lamps may decrease emissions.

From a climate standpoint, ideal targets for BC mitigation co-emit little OC, so that there is confidence that reduction of PM emissions reduces climate warming. For economic effectiveness, alternatives capable of eliminating significant emissions at low cost are needed. For equity considerations, end-users should obtain significant benefits from the replacement, in efficiency, quality of life, and health. **Table 2.3.5** provides a basic comparison of the contributions of major BC sources, as well as current mitigation opportunities. Replacement of simple wick lamps scores highly in terms of low co-emissions and economy (*72, 73*). Growing evidence confirms that benefits to household air quality and human exposure are also high (*18*). Unlike many other major sources of BC, many kerosene lamps are used indoors and in close proximity to users, which means that more of their emissions are inhaled, possibly increasing the risk of several adverse health outcomes, including respiratory diseases such as tuberculosis, currently a leading cause of early mortality in developing countries (*74, 75*). Considering these characteristics, replacing simple kerosene lamps is an attractive and achievable step towards reduce warming by short-lived climate forcers.

Table 2.3.5 Characteristics of major BC sources and associated mitigation opportunities

Source category	Fraction of global BC emissions[1]	Annual BC emissions (Gg)[1]	Major co-emissions[2]	Potential Interventions[3]
Kerosene lamps	3%	270 (110, 590)	None	LED or more efficient fuel-based lamps (e.g. pressure, hurricane)
Diesel engines	17%	1320 (530, 2400)	NO_x (-)	Particle traps, retrofit, standard introduction
Residential solid fuel	24%	1880 (480, 5300)	OM (-)	Efficient stoves, improved combustion, fuel switching
Industrial coal	12%	740 (160, 2800)	SO_2 (-)	Process modernization
Open biomass burning	40%	2750 (980, 12000)	OM (-)	Suppression, controlled burning with capture

[1] Values in parentheses represents 90% uncertainty bounds

[2] Symbols in parentheses represents the direction of forcing (+/-) for co-emissions, OM = organic matter which is cooling (

[3] Only the possibilities with greatest mitigation potential are listed here

BC annual emissions and uncertainty bounds obtained from procedures in Bond et al. (2004), with updates as described in Lamarque et al. (2011) (*76*) The exception is kerosene lamps, which are based on results from this study

2.3.7 Comparison to Previous Emission Estimates

The emission estimates presented here may be low for several reasons. The annual estimate of kerosene consumption for residential lighting is less than one-tenth of that given by Mills (65,000 Gg kerosene/year) (*15*) and approximately one quarter of those estimated by the UN EnLighten Initiative. A comparison of the methods provides two major differences between study estimates: this study applied information from national household surveys to arrive at a more constrained number of households reliant on kerosene as opposed to assuming that all non-electrified households use kerosene. For the first pioneering estimates of emissions, for example, Mills uses electricity access as a proxy for kerosene use. Second, this study applied a fuel burn rate based on laboratory and field measurements of simple wick lamps measured in lab and field samples. These burn rates are roughly four times lower that that used by many assessments, including both the EnLighten and Mills (2005) estimates. There are also other reasons which may add to underestimation. Fuel impurities are known to decrease combustion efficiency and kerosene used in lab measurements is likely representative of the cleanest consumer kerosene. Finally, in this study, emissions from the following sources were ignored: lighting in non-household settings, such as schools, restaurants, and by street vendors and, except for India, in households with intermittent access to electricity. Chapter 4 explores the potential contribution of secondary demand for lighting using self reported survey information.

The national lighting program in India (labl.teriin.org) and efforts in several African countries (www.lightingafrica.org) are currently developing and deploying low-cost LED lamps in populations that currently rely on kerosene and other fuel-based lighting sources due to limited or non-existent access to electricity. From a climate standpoint, these pico-solar systems have been estimated to have a payback period on the order of 20-50 days, depending on the complexity of the system.

If these programs are successful, developing countries will have made a substantial contribution to reducing global warming and improving human welfare. I explore some of these potential benefits in India in subsequent chapters, as well as filling some of the information gaps identified in this study, specifically the role of secondary demand for lighting.

2.4 References

1. IEA, "Energy for all: Financing access for the poor " *Energy Outlook 2011* (International Energy Agency, Osolo 2011).
2. S. Mehta, C. Shahpar, The health benefits of interventions to reduce indoor air pollution from solid fuel use: a cost-effectiveness analysis. *Energy for Sustainable Development* **8**, 53-59 (2004).
3. C. Venkataraman, G. Habib, A. Eiguren-Fernandez, A. H. Miguel, S. K. Friedlander, Residential biofuels in South Asia: Carbonaceous aerosol emissions and climate Impacts. *Science* **307**, 1454-1456 (2005).
4. V. Ramanathan, G. Carmichael, Global and regional climate changes due to black carbon. *Nature Geosci.* **1**, 221-227 (2008).
5. J. E. Penner, C. C. Chuang, K. Grant, Climate forcing by carbonaceous and sulfate aerosols. *Clim. Dynam.* **14**, 839-851 (1998).
6. T. C. Bond, C. Zarzycki, M. G. Flanner, D. M. Kock, Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse. *Atmos. Chem. Phys.* **11**, 1505-1525 (2011).
7. J. E. Hansen, M. Sato, R. Ruedy, A. Lacis, V. Oinas, Global warming in the twenty-first century: an alternative scenario. *Proceedings of the National Academy of Sciences of the United States of America* **97**, 9875-9880 (2000).
8. M. Z. Jacobson, Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *J. Geophys. Res.* **107**, 4410-4432 (2002).
9. V. Ramanathan, Y. Feng, On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *Proc. Nat. Acad. Sci. USA* **105**, 14245-14250 (2008).
10. D. Shindell, J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes *et al.*, Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335**, 183-189 (2012).
11. C. Schultz, I. Platonova, G. Doluweera, D. Irvine-Halliday, paper presented at the Eighth International Conference on Solid State Lighting, 2008.
12. D. V. Spracklen, K. S. Carslaw, U. Poschl, A. Rap, P. M. Forster, Global cloud condensation nuclei influenced by carbonaceous combustion aerosol. *Atmos. Chem. Phys.* **11**, 9067-9087 (2011).
13. S. E. Bauer, S. Menon, D. Koch, T. C. Bond, K. Tsigaridis, A global modeling study on carbonaceous aerosol microphysical characteristics and radiative forcing. *Atmos. Chem. Phys.* **10**, 4543-4592 (2010).
14. R. E. Kopp, D. L. Mauzerall, Assessing the climatic benefits of black carbon mitigation. *Proc. Nat. Acad. Sci. USA* **107**, 11703-11708 (2010); published online EpubJun.
15. E. Mills, The specter of fuel-based lighting. *Science* **308**, 1263-1264 (2005); published online EpubMay 27, 2005.
16. S. Schare, K. R. Smith, Particulate emission rates of simple kerosene lamps. *Energy for Sustainable Development* **2**, 32-35 (1995).

17. C. Fan, J. Zhang, Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures. *Atmos. Environ.* **35**, 1281-1290 (2001).
18. J. Apple, R. Vicente, A. Yarberry, N. Lohse, E. Mills, A. Jacobson, D. Poppendieck, Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air* **20**, 399-411 (2010).
19. W. P. Arnott, H. Moosmuller, J. W. Walker, Nitrogen dioxide and kerosene-flame soot calibration of photoacoustic instruments for measurments of light absorption by aerosols. *Rev. Sci. Instrum.* **71**, 4545-4552 (2000).
20. L. W. A. Chen, H. Moosmuller, W. P. Arnott, J. C. Chow, J. G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, W. M. Hao, Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles. *Environ Sci Technol* **41**, 4317-4325 (2007).
21. C. A. Roden, T. C. Bond, S. Conway, A. B. O. Pinel, Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. *Environ Sci Technol* **40**, 6750-6757 (2006); published online Epub2006/11/01.
22. NIOSH, "Diesel particulate matter (as Elemental Carbon). NIOSH Manual of Analytical Methods 5040, Issue 3," (2003).
23. T. W. Kirchstetter, C. E. Corrigan, T. Novakov, Laboratory and field investigation of the adsorption of gaseous organic compounds onto quartz filters. *Atmos. Environ.* **35**, 1663-1671 (2001).
24. B. J. Turpin, J. J. Huntzicker, S. V. Hering, Investigation of organic aerosol sampling artifacts in the Los Angeles Basin. *Atmos. Environ.* **28**, 3061-3071 (1994).
25. K. R. Smith, R. Uma, V. V. N. Kishore, K. Lata, V. Joshi, J. Zhang, R. A. Rasmussen, M. A. K. Khalil, "Greenhouse gases from small-scale combustion devices in developing countries: Phase IIA, Household stoves in India," (US EPA, Washington DC, 2000).
26. D. E. Ward, R. A. Susott, R. E. Babbitt, R. W. Shea, J. B. Kauffman, C. O. Justice, Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems. *J. Geophys. Res.-Atmos.* **101**, 23569-23576 (1996).
27. T. W. Kirchstetter, B. C. Singer, R. A. Harley, G. R. Kendall, W. Chan, Impact of Oxygenated Gasoline Use on California Light-Duty Vehicle Emissions. *Environmental Science & Technology* **30**, 661-670 (1996); published online Epub1996/01/01.
28. IEA, *Energy statistics of OECD countries*. (International Energy Agency, 2007).
29. IEA, *Energy statistics of non-OECD countries*. (International Energy Agency, 2007).
30. L. Zhang, Z. Yang, B. Chen, C. Chen, Rural energy in China: Pattern and policy. *Renew. Energ.* **34**, 2813-2823 (2009).
31. IFC/WB, "Quantitiative Assessement - Ethiopia " *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008a).

32. IFC/WB, "Quantitiative Assessement - Kenya," *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008c).
33. Demographic and Health Surveys. (U.S. Agency for International Development and ICF International, 2012).
34. Minnesota Population Center, *Integrated Public Use Microdata Series, International: Version 6.1 [Machine-readable dataset]*. (University of Minnesota, Minneapolis, 2011).
35. K. Ismail, M. Khlafala, "Sudanese 2008 Census Report: Household and Housing Characteristics," (Central Bureau of Statistics Sudan, Khartoum, 2009).
36. Uganda Bureau of Statistics, "Uganda National Household Survey 2009/2010," (Kampala, Uganda, 2010).
37. IFC/WB, "Quantitiative Assessement - Zambia," *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008).
38. Statistics South Africa, "General household survey," (Statistics South Africa, Pretoria, 2011).
39. CSO Swaziland, "Poverty in a decade of slow economic growth: Swaziland in the 2000's," (Central Statistical Office of Swaziland Mbabane, 2011).
40. IFC/WB, "Quantitiative Assessement - Tanzania," *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008d).
41. IFC/WB, "Quantitiative Assessement - Ghana," *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008b).
42. NBS Nigeria, "General Household Survey 2006, Third Edition," (National Bureau of Statistics, Federal Government of Nigeria Abuja 2006).
43. Statistics Sierra Leone, "Sierra Leone Integrated Household Survey (SLIHS) 2003/2004," (Statistics Sierra Leone and Department for International Development, 2007).
44. DIGESTYC, "Censo de Población y Vivienda 2007 (Viviendas): Condicion de ocupacion " *Censo de Población y Vivienda 2007* (Dirección General de Estadística y Censos (DIGESTYC), República de El Salvador, San Salvador, 2007).
45. INE Honduras, "Censo 2001: Datos del hogar," *Censo 2001* (Instituto Nacional de Estadistica y Censos, Honduras, Tegucigalpa, 2001).
46. INIDE Nicaragua, "VIII Censo de Población y IV de Vivienda, 2005," *Censos Nacionales* (Instiuto Nacional de Informacion de Desarrollo (INIDE), Managua 2005).
47. INE Panama, "Censos de Población y Vivienda de Panamá: Año 2010 (Caracteristicas de los hogares)," *Censos de Población y Vivienda de Panamá: Año 2010* (Instituto Nacional de Estadística y Censo, Panama City, 2010).
48. ECLAC, "Characteristics of households with ICTs in Latin America and the Caribbean " *ECLAC- Project Documents collection* (ECLAC / ICA-DRC /LIS, New York, 2007).

49. DANE, "Censo 2005: Poblacion, hogar y viviendo (Colombia)," *Censo 2005* (Departamento Administrativo Nacional de Estadistica (DANE), Bogotá, 2005).
50. INEI Peru, "Censo de Poblacion y Vividenda 2007," *Censos Nacionales: XI de Población y VI de Vivienda 2007* (El Instituto Nacional de Estadística e Informática Lima, 2007).
51. M. Asaduzzaman, D. F. Barnes, S. R. Khandker, "Restoring balance: Bangladesh's rural energy realities " *Energy and Poverty* (The International Bank for Resconstruction and Development/The World Bank Group, Washington D.C., 2009).
52. NSSO, "Energy sources of India household for cooking and lighting, NSS 61st Round (July 2004 - June 2005), Report No. 511 (61/1.0/4)," (National Sample Survey Organisation New Dehli, 2007).
53. B.-S. Indonesia, "Statistik Indonesia: Statistical yearbook of Indonesia 2011," *Statistical yearbook of Indonesia* (Badan Pusat Statistik, Jakarta, 2011).
54. NSSO, "Household consumption of various goods and services in India, NSS 61st Round (July 2004 - June 2005), Report No. 509 (61/1.0/2)," (National Sample Survey Organisation, New Dehli, 2007).
55. A. Chaurey, T. C. Kandpal, Carbon abatement potential of solar home systems in India and their cost reduction due to carbon finance. *Energ. Policy* **37**, 115-125 (2009).
56. D. Palit, A. Chaurey, Off-grid rural electrification experiences from South Asia: Status and best practices. *Energy Sustain. Dev.* **15**, 266-276 (2011).
57. UNFCC CDM, "Clean Development Mechanism Project Design Document Form: Rural Education for Development Society (REDS) CDM Photovoltaic Lighting Project (46071123)," (UNFCC Clean Development Mechanism, 2009).
58. C. More, S. Saikia, R. Banferjee, An analysis of Maharashtra's power situation *Economic and Political Weekly* **42**, 3943-3951 (2007).
59. G. Habib, C. Venkataraman, T. C. Bond, J. J. Schauer, Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels. *Environ Sci Technol* **42**, 8829-8834 (2008).
60. IFC/WB, "Quantitiative Assessement - Ethiopia " *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008).
61. IFC/WB, "Quantitiative Assessement - Zambia," *Lighting Africa Market Assessment Results* (International Finance Corporation and The World Bank, 2008e).
62. D. L. Liu, W. W. Nazaroff, Modeling pollutant penetration across building envelopes. *Atmosph. Environ.* **35**, 4451-4462 (2001).
63. W. J. Riley, T. E. McKone, A. C. K. Lai, W. W. Nazaroff, Undoor particuate matter of outdoor origin: Importnce of size-dependent removal mechanisms. *Environ. Sci. Technol.* **36**, (2002).
64. T. C. Bond, D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo, Z. Klimont, A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* **109**, D14203 (2004).
65. T. C. Bond, R. W. Bergstrom, Light absorption by carbonaceous particles: An investigative review *Aerosol Sci. Technol.* **40**, 27-67 (2006).

66. Z. Lu, Q. Zhang, D. G. Streets, Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996-2010. *Atmos. Chem. Phys.* **11**, 9839-9864 (2011).
67. D. Koch, M. Schulz, S. Kinne, C. McNaughton, J. R. Spackman, Y. Balkanski, S. Bauer, T. Berntsen, T. C. Bond, O. Boucher *et al.*, Evaluation of black carbon estimations in global aerosol models. *Atmos. Chem. Phys.* **9**, 9001-9026 (2009).
68. S. Menon, D. Koch, G. Beig, S. Sahu, J. Fasullo, D. Orlikowski, Black carbon aerosols and the third polar ice cap. *Atmos. Chem. Phys.* **10**, 4559-4571 (2010).
69. R. R. Dickerson, M. O. Andreae, T. Campos, O. L. Mayol-Bracero, C. Neusuess, D. G. Streets, Analysis of black carbon and carbon monoxide observed over the Indian Ocean: Implications for emissions and photochemistry. *J. Geophys. Res.-Atmos.* **107**, (2002); published online EpubSep-Oct.
70. P. K. Quinn, T. S. Bates, North American, Asian, and Indian haze: similar regional impacts on climate? *Geophys. Res. Lett.* **30**, 1555 (2003).
71. C. E. Chung, V. Ramanathan, G. Carmichael, S. Kulkarni, Y. Tang, B. Adhikary, L. R. Leung, Y. Qian, Anthropogenic aerosol radiative forcing in Asia derived from regional models with atmospheric and aerosol data assimilation. *Atmospheric Chemistry and Physics* **10**, 6007-6024 (2010).
72. E. Mills, A. Jacobson, From carbon to light: a new framework for estimating greenhouse gas emissions reductions from replacing fuel-based lighting with LED systems. *Energ. Effic.* **4**, 523-546 (2011).
73. E. Adkins, S. Eapen, F. Kaluqile, G. Nair, V. Modi, Off-grid energy services for the poor: Introducing LED lighting in the Millenium Village Project in Malawi. *Energ. Policy* **38**, 1087-1097 (2011).
74. N. L. Lam, K. R. Smith, A. Gauthier, M. N. Bates, Kerosene: a review of household uses and their hazards in low- and middle-income countries. *Journal of Toxicology and Environmental Health, Parth B: Critical Reviews* **15**, 396-432 (2012).
75. A. K. Pokhrel, M. N. Bates, S. C. Verma, H. S. Joshi, C. T. Sreeramareddy, K. R. Smith, Tuberculosis and Indoor Biomass and Kerosene Use in Nepal: A Case-Control Study. *Environ Health Perspect* **118**, (2010).
76. J. Lamarque, T. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, Historical(1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.* **10**, 7017-7039 (2010).

3.0 Chapter 3

Area Concentrations and Markers of Pollution: Household Cooking and Lighting Devices in Kaski District, Nepal

3.1 Introduction

Household combustion sources generate complex pollutant mixtures, requiring the use of markers of pollution (markers) to serve as surrogates for the hundreds or thousands of co-emitted, but unmeasured, pollutant species. Markers also play a critical role during the design of control strategies (e.g. air quality standards, emission standards), and may be used to provide an initial assessment of the potential health risk posed by a suspected pollutant source. Markers are imperfect, however. The components of mixtures relevant to health outcomes may not be identified, and therefore identifying a suitable marker can present challenges. Broad application of markers without validation can lead to misleading conclusions, especially when exposures to different complex mixtures are evaluated with the same markers and interpreted in the same manner. Therefore, application and selection of markers can be continuously improved upon. This is especially true in household energy projects where exposure assessment has been reliant on very few markers, yet fuel use diversity and fuel mixing can lead to a variety of complex mixtures.

Improvements in sampling technology and analytical techniques have made it easier and more affordable to apply a wider range of markers within household air pollution assessments. In this study, selected markers of air pollution are used during the operation of typical cooking and lighting devices used in households in the Kaski District of Nepal. Trends and concentrations of common markers currently used in household air pollution assessments ("standard" markers) are compared to two less frequently used markers ("supplemental" markers). Results are used to determine whether supplemental markers provide additional information not provided by standard markers alone.

3.1.1 Markers of Pollutant Exposure

Markers are specific pollutants or pollutant characteristics that serve as surrogates for hundreds or thousands of unmeasured co-emitted species. Although some markers pose direct health risk (active-agents), apportioning and distilling effects to an individual set of active agents in a complex mixture is difficult in many circumstances, given the knowledge of pollutant toxicities and interactions required. There is no governing set of criteria for identifying an effective marker, however, attributes of an ideal marker have been summarized to exhibit several characteristics (*1*). First, levels of the marker should be proportional to (other) known active agents in the complex mixture. Thus, (second) there should be few exogenous sources of the marker or active agents that could alter the marker-agent relationship. Third, related to the previous points, the marker should be stable over the timescale of interest; this has traditionally been an issue associated with ambient pollutants, but less of a concern for household-level exposures.

Markers are often developed under specific pollutant or environmental contexts, but subsequently applied across a range of different scenarios to serve the same purpose. Application of markers out of their original context and without some level of validation, however, can add to measurement uncertainty or provide little to no information. Particle mass concentrations, for example, are among the most widely used exposure indicators of health risk, especially for evaluating exposure to pollutants from combustion. In the household energy literature, carbon monoxide (CO) has sometimes been used as a proxy for PM emitted by woodsmoke, based on strong associations between long-term (24-hr) environmental averages (*2, 3*). However, CO has been shown to be a a poor marker for PM in households using charcoal stoves, and relationships derived from long-term averages may be inaccurate when applied at shorter timescales representing different phases of the combustion cycle (*4*).

For evaluating exposure or environmental concentrations in household settings, measurement campaigns have historically relied on non-pollutant indicators in the form of self-reported questionnaires (e.g., stove types, usage), or two objective markers of pollution: $PM_{2.5}$ and carbon monoxide ("standard markers"). Non-pollutant markers can be time- and cost-efficient, but used alone, are limited in their ability to relate observed health effects to exposure concentrations, attribute exposure to pollutant sources, or develop exposure-response relationships. $PM_{2.5}$ is the most common, and often sole, pollutant measure regardless of the complex mixture in question, while CO is often used as a lower cost marker for $PM_{2.5}$, especially for personal exposure measurements (*2, 5*). Despite improvements in sampling technology and analytical techniques, there has been little effort to expand the relativity small set of markers applied in studies on household air pollution.

3.1.2 Polycyclic Aromatic Hydrocarbons

One class of combustion products that has seen a resurgence of interest in the exposure and marker literature is polycyclic aromatic hydrocarbons (PAHs). PAHs are formed from the incomplete combustion or pyrolysis of organic materials and embody a class of compounds that are typically monitored by quantifying a subset of species selected on the basis of their toxicity or relationship to sources. PAHs composed of 2-3 benzene rings have vapor pressures high enough to exist almost exclusively in the vapor phase, while those with greater than 4 rings typically exist in the particle phase (particle-bound). Partitioning between phases occurs for PAHs with 3-4 rings, depending on environmental conditions.

There are several characteristics that make PAHs an attractive marker for evaluating complex mixtures. PAHs are generated by combustion, and as a class of compounds, can provide a numerous pollutant measures from a single piece of sample media. A growing body of evidence has also begun to link PAH effects via toxicological mechanisms. A recent study, for example, showed that increased methylation of CpG islands of the Foxp3 gene in T_{reg} cells is associated with reduced IFN-γ protein expression, which inhibits the ability of T_{reg} cells to fight infections (*6*). Estimates of ambient PAH concentrations were shown to have a positive association with these epigenetic changes in the T_{reg} cells (*6*). Of relevance to one specific health outcome, activation of tuberculosis has been linked to reduction in IFN-γ (*7*), while T_{reg} cells have been shown play a role in the regulation of immunity and immune response in patients with active TB (*8*). Thus, PAH has the benefit of being a marker of a complex mixture and potential active agent.

Use of PAHs as markers of complex mixtures is not new in the broader context of air pollution exposure and human health risk assessment. Benzo-a-pyrene, for example, has been applied as an indicator of carcinogenicity and mutagenicity of mixtures for over three decades and justified by a substantial body of toxicological evidence based on assays and animal models. Efforts to develop toxic equivalency factors relative to benzo-a-pyrene (TEFs), sometimes referred to as potency equivalency factors (PEFs), have been used to capture the cancer risk associated with co-emitted PAH (*9-12*). Since the levels of benzo-a-pyrene relative to other PAH were known to vary across different complex mixtures, the TEF could also provide a more robust multi-pollutant index. Current TEF estimates of commonly measured PAH span three orders of magnitude, ranging from unity, or equivalent to benzo-a-pyrene (e.g. dibenzo(a,h)anthracene), to 0.005 (e.g. anthracene, phenanthrene) (*12, 13*). Application of benzo-a-pyrene and associated TEFs as markers, however, are founded on their effect as carcinogens. Thus, it is unclear whether these markers would be representative of non-cancer outcomes, such as the potential effect of PAH on immunosuppression recently identified (*6*).

Differences in the relative abundance of PAH (PAH profiles) have been utilized in the aquatic and air pollution literature for several decades to construct source diagnostic ratios (DR). As opposed to health indicators, DRs provide a quantitative threshold for detecting the presence and dominance of specific PAH sources by leveraging source differences in the relative proportions of PAH species. The most common ratios consist of PAHs of equal mass but differing configuration (isomers) signifying differences in stability during formation or in the environment (*14*). For example, theoretical models and laboratory experiments have indicated that the Phenanthrene/Anthracene (PHE/ANT) ratio is inversely related to combustion temperature (*15, 16*). This physical characteristic has been used to distinguish between petrogenic (PAHs from the parent fuel) and pyrogenic (combustion derived) PAHs in soil samples. In the household context, temperature effects of diagnostic ratio values might be useful for distinguishing activities with different combustion conditions – such as lighting and cooking. A Fluoranthene/(Fluranthene+Pyrene) ratio greater than 0.5 has been used to distinguish between PAH samples dominated by diesel versus gasoline emissions (*17-21*). At a coarser level of source resolution, a Fluoranthene/Pyrene ratio of 0.6 has been used as a cutoff for general vehicular emissions in urban air samples (*16, 19*).

3.1.3 Study Objectives

What follows are results from a set of pilot experiments nested within a larger study (Kaski Air Pollution Study, KAPS) that is investigating the risk of household air pollution on tuberculosis risk. The project is a follow-up investigation for a study published by Pokhrel et al. (2010), which found that among women, the odds of tuberculosis from using kerosene as a primary lighting or cooking fuel were nine and three times higher, respectively, than use of solid fuels for cooking (*22*). Indoor particulate matter (PM) measurements in homes using kerosene stoves, however, suggest that concentrations are generally much lower than those using biomass (*23*) and a simple modeling exercise would suggest that differences in particulate matter (PM) alone are not sufficient to explain the observed levels of effect (see **Appendix 6.1.1**).

This study employs controlled experiments to simultaneously measure "standard markers" of pollution ($PM_{2.5}$, total suspended particles, CO), and a set of "supplemental markers" of pollution (PAH, elemental carbon, organic carbon) during operation of common combustion appliances used by households in Kaski district of Nepal.

- Average pollutant concentrations are reported and compared across appliances. Results are used to evaluate whether trends in supplemental markers add additional information not captured by standard markers of pollution.

- PAH diagnostic ratios are constructed to explore their potential as pollutant source indicators in household exposure assessments

- Sensitivity of a commercially available continuous-reading PAH monitor (PAS 2000CE, League City, TX) to different complex pollutant mixtures is evaluated by comparison against PAH concentrations based on chemical speciation.

3.2 Methods

Experiments were performed test facility adjacent to the local field office of the Kaski Air Pollution Study (KAPS) in Pokhara, Nepal during May and June of 2013.

3.2.1 Cooking and Lighting Devices

Test appliances were chosen based on their prevalence of use in surrounding communities currently and in the last 5-10 years. Appliance selection took into account gaps in the literature pertaining specifically to emissions and exposure concentrations to basic pollutant indicators ($PM_{2.5}$, CO) and polycyclic aromatic hydrocarbons (PAHs).

A total of three cooking devices and two fuel-based light sources were measured (**Table 3.2.1**). The "U-shaped" chulo is considered as the local traditional stove. The stove is typically fueled with wood and is built by the household from mud and locally purchased materials. A metal support stand is placed within the combustion zone to elevate the pot. These stoves are semi-permanent (not mobile) and are re-built periodically. A staff member who had previously built such a stove in his home constructed the chulo used for testing.

Two kerosene stove designs are commonly found in households: a pressure-type and wick-type design. Based on local surveys, the pressure-type stove is the most widely used design in the study population. A locally constructed top loading updraft (TLUD) stove fueled by either sawdust or rice husk had also become popular in recent years, and was also included. Both stoves and respective fuels were purchased locally. Two fuel-based lighting sources were tested: a kerosene wick lamp and paraffin[1] candles. Kerosene lighting has been used widely in the region historically as a primary and backup source of lighting in homes. In recent years, removal of the kerosene subsidy has made kerosene less affordable, prompting more use of paraffin candles.

Table 3.2.1. Cooking and lighting sources

	Appliance	Code	Task/Activity	Fuel (As Tested)
1.	Mud Chulo (Traditional)	CBNC	Cooking	Wood (pine)
2.	Pressurized Kerosene Stove	CKPS	Cooking	Kerosene[1]
3.	Metal Sawdust Stove	CWHS	Cooking	Sawdust (pine)[*]
4.	Simple Wick Lamp	LKWS	Lighting	Kerosene[1]
5.	Candles	LCAN	Lighting	Paraffin[1]

[*] Rice husks are also used seasonally but were not available at the time of testing

[1] Kerosene is often considered a synonym for paraffin when sold in various parts of the world. In this document, the term paraffin refers to the wax derivative of petroleum as opposed to the kerosene fuel used in cookstoves and lighting.

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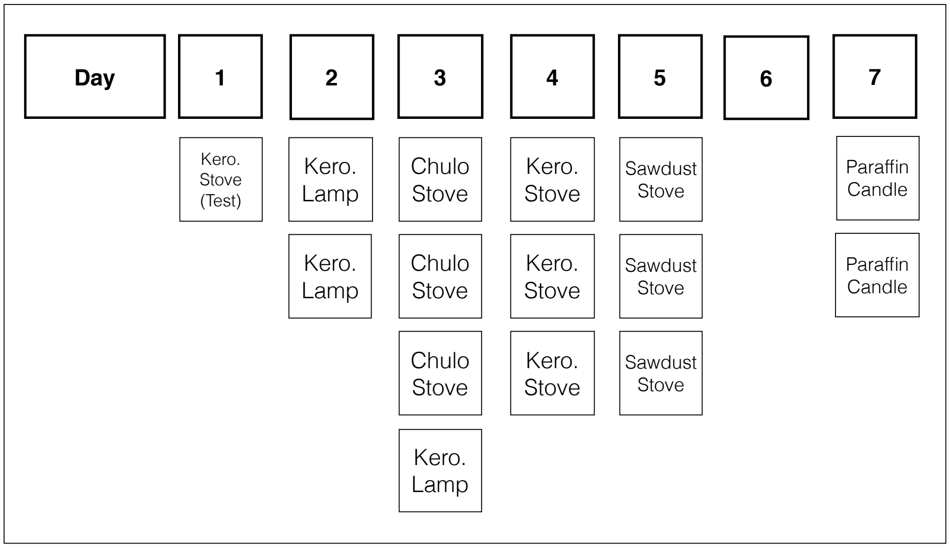
3.2.1.1 *Device Operating Procedures*

Operation of cooking and lighting appliances was performed by local staff familiar with their operation or by trained staff members. Once lit, individuals only re-entered the room to fuel devices or perform periodic checks of the measurement equipment. Cooking stoves were operated with a metal pot filled with two liters of water placed above the combustion zone. Lighting devices were allowed to burn openly in the room. The duration of each experiment varied from between 40-60 minutes. Considering pre- and post experiment QA/QC procedures, each experiment required approximately 3 hours, allowing for 3-4 experiments per day. Each appliance was tested with a full set of pollutant measures in triplicate, with the exception of the paraffin candle due to a shortage of filter media. **Table 3.2.2** outlines the final number of experiments performed on each appliance and **Figure 3.2.1** presents a day-by-day sample schedule.

Table 3.2.2. Appliance test sample sizes

	Chulo (Wood)	Kerosene Stove[1]	Sawdust Stove	Kerosene Lamp	Paraffin Candle[2]
Experiments (n)	3	4	3	3	2

[1] *one experiment had multiple restarts because of stove malfunction and was excluded from final analysis*
[2] *only one experiment was sampled with full PAH set (e.g. XAD filters, tubes) due to media shortages*



Day	1	2	3	4	5	6	7
	Kero. Stove (Test)	Kero. Lamp	Chulo Stove	Kero. Stove	Sawdust Stove		Paraffin Candle
		Kero. Lamp	Chulo Stove	Kero. Stove	Sawdust Stove		Paraffin Candle
			Chulo Stove	Kero. Stove	Sawdust Stove		
			Kero. Lamp				

Figure 3.2.1. Experiment sample schedule.

3.2.2 Room Conditions

Appliances were placed in the corner of the room furthest from the door and window, as indicated in **Figure 3.2.2**. Cooking stoves were placed on the floor and illumination sources raised from the ground so that their height relative to the pollutant-sampling tree was similar to that of an individual using the light source. The middle of all appliances were 1.0 meter horizontal from the sampling tree

Experiments were conducted in a 15m^3 room located on the grounds of the KAPS field office. Room characteristics were meant to be representative of kitchens and rooms within houses of participants in the KAPS study. The room was constructed of cinderblocks and had an angled sheet metal roof. A single door and a window, which measured approximately 1m x 0.5m, provided ventilation. Both the door and window were left open during experiments and a small fan was used to provide additional air movement. **Figure 3.2.1** is a schematic of the room in which experiments were conducted.

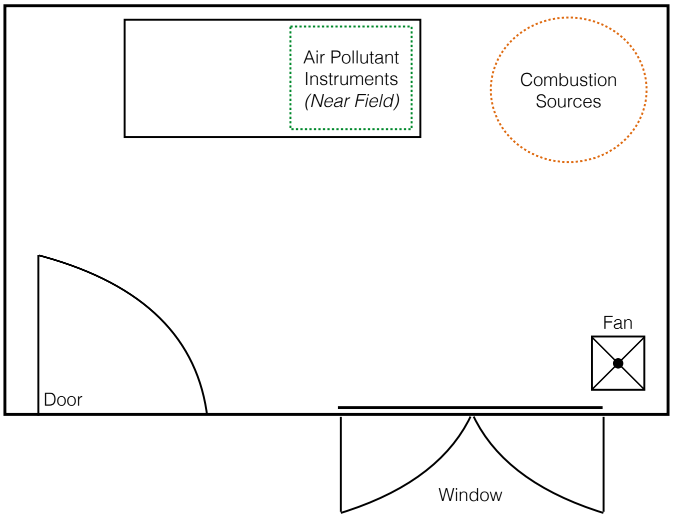


Figure 3.2.2. Schematic of room used for stove and lamp testing. Instrument and appliance placement locations are indicated with dashed lines.

3.2.2.1 Room Air Changes (AER)

At experimental conditions, the room air exchange rate was estimated to be between 3-4 per hour. AER experiments were conducted only once midway through the sample campaign so there is no information of the extent of intra- or inter-day variability. AER was estimated by calculating the decay rate following a bolus emission of 98% CO_2. For this procedure, compressed CO_2 is released into the center of the room for 10-12 seconds to achieve indoor concentrations several times greater than background (e.g. 2000 ppm). A small fan is used to provide even mixing of the gas. CO_2 concentrations are monitored at the center of the room using an array of four COZIR nondispersive infrared (NDIR) sensors operating at a logging rate of 2 Hz (EME Systems, Berkeley CA). Using concentrations during the decay period, the air exchange rate (time^{-1}) can be calculated by re-arranging the exponential decay function, $C_t = C_0 exp^{-\alpha t}$, to solve for the first order loss rate (α):

$$\frac{-\ln\left(\frac{C_t}{C_o}\right)}{t} = \frac{\ln(C_o) - \ln(C_t)}{t} = \alpha$$

Where C_t is the background adjusted CO_2 concentration t time-steps from the relative starting point with concentration C_o (background adjusted). Since CO_2 is a stable gas and background levels are approximately constant, it can be assumed that all losses from the room are due to ventilation ($\alpha_{total} = \alpha_{ventilation}$). An alternative method for obtaining an estimate of the air changes is to calculate the coefficient from a regression of real-time background-adjusted concentration on time.

3.2.3 Pollutants and Measurement Methods

Indoor concentrations of several pollutants were monitored during experiments to provide measures of pollutant concentrations and relationships during operation of selected appliances. "Standard" pollutant measures, including $PM_{2.5}$, total suspended particles (TSP), and carbon monoxide (CO), were supplemented with measures of vapor and particle phase polycyclic aromatic hydrocarbons (PAHs) based on several measurement techniques. Sample inlets for active samplers were arranged on a sampling "tree" such that they were approximately 1.0 meter from the center of the combustion source and 1.5 meter from the ground. **Figure 3.2.3** illustrates the sample tree relative to combustion zone (left panels) and the sample train components (right box). Each component is described in greater detail in subsequent sections. **Table 3.2.3** presents a matrix of which pollutants were measured over the 15 experiments.

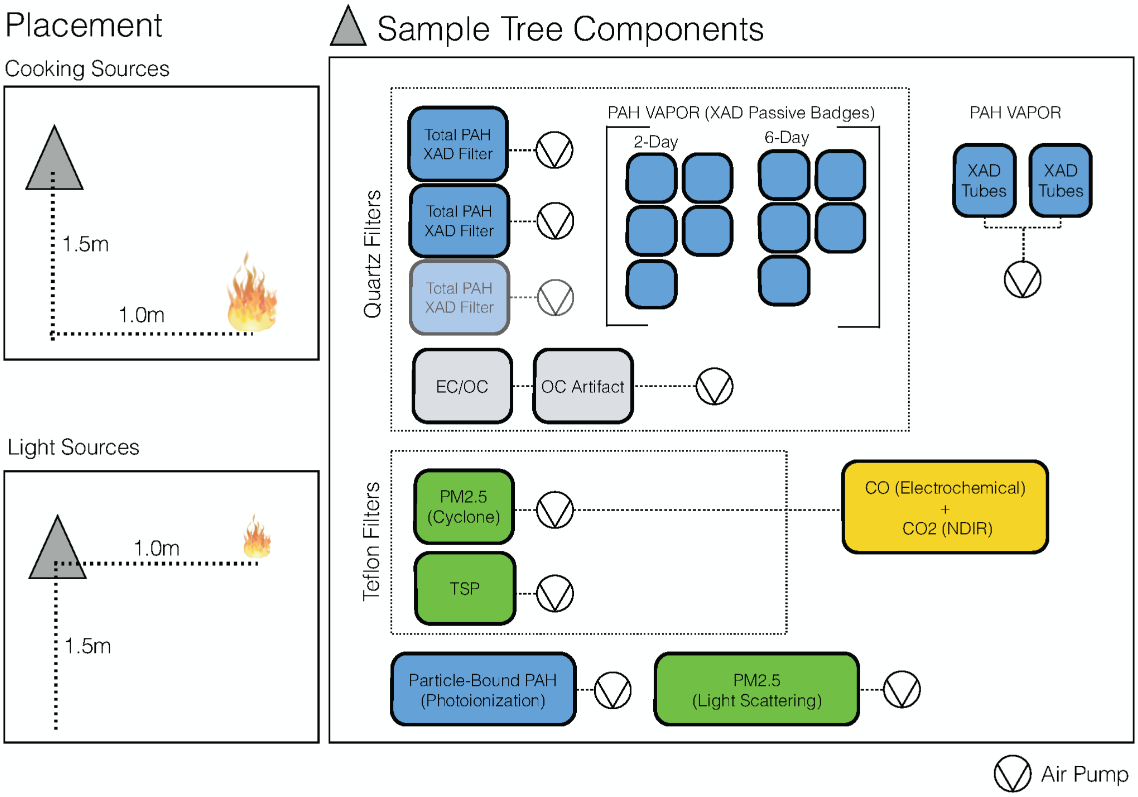


Figure 3.2.3. Schematic of sample tree placement (left panels) and suite of pollutant monitor samplers (right box). Measures of polycyclic aromatic hydrocarbons (PAHs) are represented in blue, while green and gold represent particle mass concentrations and non-PAH gases, respectively.

Table 3.2.3. Pollutant sample matrix

				Active XAD Filter			Active XAD Tube			PASS 2000	Gravimetric		EC/OC	IAQ-CALC	DustTrak
Test ID	**Sample Date**	**Device**	**Device ID**	Sing.	Dup.	Trip.	Sing.	Dup.	Trip.	(TSP)	PM2.5	TSP		CO	PM2.5
Cooking															
Sup_001	21-May-13	Kerosene Pressure Stove	CKPS							x	x	x		x	
SUP_008	23-May-13	Kerosene Pressure Stove	CKPS		x			x		x	x	x	x	x	x
SUP_009	23-May-13	Kerosene Pressure Stove	CKPS		x			x		x	x	x	x	x	x
SUP_010	23-May-13	Kerosene Pressure Stove	CKPS		x			x		x	x	x	x	x	x
SUP_011	24-May-13	Sawdust Stove	CWHS		x			x		x	x	x	x	x	x
SUP_012	24-May-13	Sawdust Stove	CWHS		x			x		x	x	x	x	x	x
SUP_013	24-May-13	Sawdust Stove	CWHS			x		x		x	x	x	x	x	x
SUP_004	22-May-13	Chula Wood Stove	CBNC		x			x		x	x	x	x	x	x
SUP_005	22-May-13	Chula Wood Stove	CBNC		x			x		x	x	x	x		x
SUP_006	22-May-13	Chula Wood Stove	CBNC			x		x		x	x	x	x		x
Lighting															
SUP_002	21-May-13	Simple Wick Lamp	LKWS			x		x		x	x	x	x	x	x
SUP_003	21-May-13	Simple Wick Lamp	LKWS		x			x		x	x	x	x	x	x
SUP_007	22-May-13	Simple Wick Lamp	LKWS		x			x		x	x	x	x	x	x
SUP_014	26-May-13	Paraffin Candle	LCAN							x	x	x		x	x
SUP_015	26-May-13	Paraffin Candle	LCAN		x			x		x	x	x	x	x	x

****Bold** values represent samples where a single XAD filter has been analyzed*

3.2.3.1 Polycyclic Aromatic Hydrocarbons

Few household air pollution studies in middle and low-income countries have performed detailed measures of PAHs and to our knowledge, none have explored their use as source markers. Towards informing household monitoring in the larger KAPS study, several chemically based measurement methods were deployed to measure particle and vapor phase PAHs. We also test the performance of a direct-reading photoionization detector for monitoring particle-bound PAHs. Chemical analysis of PAH samples were performed in the laboratory of Professor Katharine Hammond at the University of California, Berkeley.

3.2.3.1.1 Naphthalene

Naphthalene is the lowest molecular weight PAH consisting of two fused benzene rings ($C_{10}H_8$). The mass of NAP emitted from combustion is typically greater than any other individual PAH compound, sometimes by more than an order of magnitude. As a result of this and its high vapor pressure as well as potentially other factors, the sampling efficiency of NAP by active XAD filters is low. To provide more accurate measures of NAP concentrations, low-flow XAD sorbent tubes (SKC West, Fullerton CA) were used.

Each NAP tube contains two separated regions. The sample region contains 150 mg of XAD-2, while the second region contains 75mg, and is oriented downstream in order to monitor for breakthrough. Breakthrough is assumed when mass on the downstream region is greater than 25% of the first sample region. XAD tubes are effective for sampling all vapor phase PAHs, but were used to measure only NAP in this study. Like the XAD impregnated filters, NAP adsorbed to XAD is desorbed using dicloromethane (DCM) and quantified using chromatography-mass spectrometry (GC-MS). Reported concentration values are blank adjusted and combine front and back regions.

Tubes were sampled at flow rates of 200-270 mL/min using a standard SKC personal sampling pump outfitted with a low flow adaptor (Model PCXR8, SKC West, Fullerton CA). A Teflon membrane filter was placed upstream of the tube to remove particulate matter in the sample stream. Flow rates were measured before and after each experiment with a bubble meter (Gilibrator 2, Sensidyne LP, St. Petersburg FL) and field blanks were collected at a rate of 15% relative to sample tubes.

3.2.3.1.2 Combined Vapor and Particle-Bound PAHs

Combined particle and vapor phase PAHs were measured actively with 37mm quartz fiber filters impregnated with XAD (XAD filters). Particles with PAHs bound to their surface are captured in the quartz fiber matrix, while PAHs in the vapor phase are adsorbed to the XAD. For analysis, PAHs are desorbed from filters using DCM and analyzed using GC-MS. A total of 15 PAHs were measured from XAD filters, including 15 US EPA priority PAHs and retene, a PAH marker often used as an indicator of soft wood smoke (**Table 3.2.4**). The US EPA designates a total of 129 compounds as priority pollutants based on existing evidence of health risk. Sixteen of these compounds are

PAHs. Because dozens of PAHs may be measurable in a pollutant mixture, the 16 priority PAHs are designated as a set of suggested indicator compounds. Fourteen of the 16 PAHs are measured from XAD filters, while naphthalene is also included on the priority list but is measured using XAD tubes for higher sample efficiency.

Table 3.2.4. PAH compounds measured from actively sampled XAD filters. All species with the exception of retene are US EPA priority PAHs. Ring designations of 0.5 indicate that the PAH compound contains a five membered ring in addition to six membered rings.

Compound Name	Abbrv.	Rings	Compound Name	Abbrv.	Rings
Acenaphthylene	*ACY*	2	Retene	*RET*	3.5
Acenaphthene	*ACE*	2	Benz[a]anthracene	*BAA*	4
Fluorene	*FLU*	3	Chrysene	*CHR*	4
Phenanthrene	*PHE*	3	Benzo[b]fluoranthene	*BBF*	4.5
Anthracene	*ANT*	3	Benzo[k]fluoranthene	*BKF*	*4.5*
Fluoranthene	*FLT*	3.5	Benzo[a]pyrene	*BAP*	5
Pyrene	*PYR*	4	Indenopyrene	*ICP*	5.5
			Dibenzanthracene	*DBA*	5

Actively sampled XAD filters were operated in series and the downstream filter was used to evaluate for breakthrough of vapor phase PAHs. Breakthrough is assumed when mass on the back filter is greater than 50% of the front filter. In XAD tubes, the breakthrough region of the sampler contains half the sample media and has a commonly applied breakthrough threshold of 25%. By this logic, a breakthrough region containing an equal amount of sample media (XAD) has a threshold value of 50%. XAD adsorbed to XAD and particulate matter is desorbed using solvents of various polarities and quantified using GC-MS. Reported concentration values are blank adjusted and combine front and back filter masses.

An active filter sample consistent of two 37mm XAD impregnated quartz fiber filters were sealed in tandem within a polypropylene cassette (Sure Seal, SKC West, Fullerton CA) and operated at a flow rate of 2-6 L/min (Leland Legacy Pump, SKC West, Fullerton CA) without particle size selection. Flow rates were selected to minimize risk of pump failure and informed by expected PM concentrations in the room during appliance operation. Flow rates were measured before and after each experiment with a bubble flow meter (Gilibrator 2, Sensidyne LP, St. Petersburg FL). Field blanks were collected at a rate of 8% relative to samples.

XAD filters were deployed in duplicate for two of the three device experiments and the third experiment was sampled in triplicate. The paraffin candle is an exception, for which only one experiment was conducted with XAD filters (duplicate measures). Following each experiment, filter media were immediately transferred to clean petri-dishes, sealed with Teflon tape and stored at -18 C.

3.2.3.1.3 Continuous Measures of PAH: PAS 2000CE

Particle-bound PAHs were measured in real-time using a photoionization aerosol sensor (PAS) manufactured by EchoChem Analytics (League City TX), the PAS 2000CE. The PAS relies on UV radiation (207 nm) generated by a KrBR excimer lamp to ionize (photoionize) PAHs bound to particulate matter, theoretically with diameters less than 1 micron (*24*). Negative ions formed by the emission of the electron diffuse to the walls or are removed by an electric field, while the positively charged particles are collected on a downstream filter. The electric current generated during the migration of particles is monitored with an electrometer and the signal converted to a PAH mass concentration based on an a conversion factor based on a manufacturer reference PAS monitor (*24*). In principle, however, ionization potentials across PAH species are not equal and particles with the same PAH mass but different PAH compositions may yield different photoemission signals (*25*). The PAS provides an aggregate measure of particle-bound PAHs and vapor phase PAHs are unmeasured according to manufacture literature. As a result, the PAS used alone is often cited as a "semi-quantitative" method (*26*), although absolute values can be made more interpretable by co-locating the PAS with a device collecting PAHs, which can be measured chemically.

PAS-reported concentrations were logged at 10-second intervals and zero levels checked before and after each experiment using a HEPA filter capsule. The PAS 2000CE has an internal pump that continually samples at 1.2 L/min without size selection. The unit used for sampling was returned to the manufacture, following the experiments and determined to be measuring within calibration thresholds.

3.2.3.2 <u>Particle Mass Concentrations</u>

3.2.3.2.1 Gravimetric (Filter-Based)

Gravimetric mass concentrations of total suspended particles (TSP) and $PM_{2.5}$ were measured using 37mm Teflon filters with 2um pore size. Both TSP and $PM_{2.5}$ were sampled in styrene cassettes with cellulose backup pads. TSP was sampled between 1.5-2 L/min and $PM_{2.5}$ filters at 1.5 L/min using a Triplex cyclone (BGI Inc., Waltham MA). Both TSP and $PM_{2.5}$ were actively sampled with personal sampling pumps (Model PCXR8, SKC West, Fullerton CA) and flow rates checked before and after each experiment with a bubble flow meter (Gilibrator 2, Sensidyne LP, St. Petersburg FL). Field blanks were collected at a rate of approximately 20% relative to samples.

Teflon filters were weighed before and after sampling in a temperature and humidity controlled room (21C, 40%RH) using a Mettler Toledo XP5U microbalance (Thermo Electron Corp.) at a precision of 0.5 ug.

3.2.3.2.2 Direct (Continuous) Reading

Real-time $PM_{2.5}$ concentrations were measured with a DustTrak 8520 (TSI Corp., Shoreview MN) at a sample flow rate of 1.7 L/min. The DustTrak does not directly measure particle mass but estimates it based on the light scattering of particles in the sample steam. The internal calibration factor is based on tests with Arizona road dust and thus readings from the DustTrak were adjusted with device-specific *average* correction factors based on the simultaneous gravimetric $PM_{2.5}$ measures. Because there is some variability in k-factors across tests performed on the same device, the adjusted DustTrak concentration will not match gravimetric concentrations for individual tests.

3.2.3.3 Elemental Carbon and Organic Carbon (EC/OC)

Total aerosol carbon (TC) was separated into elemental carbon (EC) and organic carbon (OC) components using a thermal-optical-transmittance method (TOT) (*27, 28*). The formation of "soot" during combustion is thought to occur through growth of PAH rings (*29*), and EC is often highly correlated with PAH concentrations (*16*). There is also some evidence, based on samples of urban aerosol, that EC may yield higher health risk estimates than undifferentiated PM mass, and should be considered as an additional marker for studies evaluating impacts of primary combustion particles (*30*). It is important to note, however, that such associations are not indicative of a causal effect and may simply be reflecting the increased risk from co-emitted species correlated with EC. EC and OC are measured here for their use as exposure markers, but also because EC may be an interference effects on the PAS 2000CE.

Aerosol carbon (TC) was collected without size selection on 47mm pre-baked quartz fiber filters in polypropylene cassettes. EC/OC was actively sampled using a personal sampling pump (PCXR8, SKC West, Fullerton CA) at a flow rate of 1.5-3 L/min. Following experiments, EC/OC filters were immediately transferred to petri dishes, sealed with Teflon tape and stored at -18C. One EC/OC sample set consisted of two filters. The "sample" filter collected all aerosol carbon. A second filter sampled downstream of a Teflon filters was used to assess for organic vapor artifact (*31*), which was subsequently subtracted from the sample filter. Thus reported values correspond to total aerosol carbon. A single sample from each device was analyzed by DRI (Oakland, CA) and final masses adjusted using field blanks. Chemical analysis was performed only on filters collected from the first experiment of each device, with the exception of the paraffin candle (2nd experiment).

3.2.3.4 Carbon Monoxide

Carbon monoxide (CO) was measured in real-time electrochemically using a TSI IAQ-Calc (Model 7525, TSI Corp., Shoreview MN). The monitor was calibrated and response checked using certified CO span gas in Berkeley, CA, prior to deployment in the field. The CO sensor on the IAQ-Calc has an operating range of 0-500ppm, resolution of 0.1 ppm CO, and manufacture specified accuracy of 3% or 3 ppm (whichever is greater). The IAQ Calc was operated under a modified arrangement that allowed for active sampling and, in theory, faster response to changing room concentrations. The outlet airstream of a personal sampling pump was fed into a cap that enclosed the entire IAQ-Calc sample probe. Particles from the sample stream were removed by the Teflon filter upstream of the pump.

3.3 Results & Discussion

3.3.1 Standard Markers of Pollution (TSP, $PM_{2.5}$, CO)

I define "standard" pollutant measures as those pollutant species that are commonly used for exposure assessments within the household energy literature. These pollutants include fine particulate matter ($PM_{2.5}$), total suspended particles (TSP) and carbon monoxide (CO). Mean concentrations of these pollutants over experiments and appliances are presented in **Table 3.3.1**. Results for $PM_{2.5}$ are also illustrated in **Figure 3.3.1.**

Table 3.3.1. Concentrations of standard markers of pollution. Device-level and experiment-level $PM_{2.5}$, TSP (ug/m^3) and carbon monoxide (CO, ppm) concentrations. Light scattering mass-concentrations from the DustTrak are adjusted using gravimetric $PM_{2.5}$. Values in parentheses represent the standard deviation across experiments with a single appliance (N=3).

		DustTrak*		***Gravimetric***		
Device	**Exp.**	**$PM_{2.5}$ (ug/m^3)**	***K-Factor*[3]**	**$PM_{2.5}$ (ug/m^3)**	**TSP (ug/m^3)**	**CO (ppm)**
Chulo Stove	**All**	**3110 (1590)**	**0.28 (0.10)**	**2970 (1710)**	**3090 (1900)**	**44 (-)**
	1	4730	0.30	4940	5272	44
	2	1550	0.38	2070	1838	ND[1]
	3	3030	0.18	1890	2162	ND[1]
Kerosene Stove	**All**	**185 (148)**	**0.40 (0.01)**	**182 (139)**	**288 (144)**	**12 (7)**
	1	350	0.38	337	454	5
	2	140	0.41	142	218	19
	3	66	0.41	68	193	12
Sawdust Stove	**All**	**914 (517)**	**0.37 (0.05)**	**956 (674)**	**778 (399)**	**24 (13)**
	1	1507	0.43	1734	1236	38
	2	672	0.33	590	508	16
	3	562	0.36	546	590	17
Kerosene Lamp	**All**	**290 (87)**	**0.13 (0.09)**	**308 (257)**	**826 (354)**	**0 (-)**
	1	345	0.08	215	866	0
	2	334	0.24	599	1158	0
	3	190	0.08	111	453	0
Paraffin Candle	**All**	**69 (-)**	**0.72 (-)**	**88 (-)**	**113 (-)**	**0 (-)**
	1	50	ND	ND[2]	ND2	0
	2	88	0.72	88	113	0

* *Raw values adjusted based on device-level average k-factors*

[1] *Data acquisition error, no data available*

[2] *Samples not collected during experiment*

[3] *k-factor = $PM_{2.5}$ DustTrak/$PM_{2.5}$ Gravimetric*

3.3.1.1 Undifferentiated Particle Mass Concentrations ($PM_{2.5}$, TSP)

Average $PM_{2.5}$ room concentrations based on gravimetrically adjusted (device specific) DustTrak measurements varied across appliances by as much as a factor of 45 (**Figure 3.3.1**). The wood-fueled chulo had the highest concentrations, averaging 3100 ug/m^3, and the paraffin candle the lowest at 69 ug/m^3, which was still roughly double the background pre-test concentration (25-30 ug/m^3). Average $PM_{2.5}$ concentrations during use of the kerosene stove was 60% lower than during kerosene lamp operation, despite a much higher rate of fuel consumption. As expected, the same trends are reflected in gravimetric analysis of $PM_{2.5}$.

The emission rate of $PM_{2.5}$, or any pollutant, can be described as the product of two parameters: an emission factor, which describes the amount of pollutant emitted per unit of consumption (e.g. mg PM/kg fuel burned), and the fuel consumption rate, which describes the rate of consumption (e.g. kg wood/hour). Final pollutant concentrations are influenced by both factors, and can be illustrated from experimental results. The kerosene lamp, for example, has a high emission factor, converting 7-10% of fuel to PM, but consumes fuel at a very slow rate (10 g/hr). Elevated $PM_{2.5}$ concentrations in this case are driven by high emission factors. Conversely, a chulo cookstove coverts far less of its fuel mass to PM (0.5-1.5%), but consumes fuel at a rate (1-2 kg/hr) that is roughly two orders of magnitude greater than the lamp (*32, 33*). The difference in the consumption rates is larger than the difference in emission factors, thus one would expect higher PM concentrations during use of the stove. Perhaps a better comparison to the lamp is the use that of the kerosene stove, which consumes fuel at a faster rate than the lamp but has a PM emission factor of roughly an order of magnitude lower. Both parameters can be affected by combustion conditions, to an extent, and highlights how different fuel-use activities can yield drastically different their final emissions. Thus, knowledge of fuel alone is not always sufficient to adequately provide emissions estimates.

Field monitors used for household and personal exposure assessment of real-time particle mass concentrations typically rely on light scattering and are sensitive to aerosol composition. Interpretation of responses as absolute concentrations is dependent upon validation against a standard reference method, typically gravimetric sampling. In the context of household energy, simple changes to the combustion efficiency can have implications for light scattering properties, even if fuels remain the same. Bias resulting from differences in source/scenario-specific aerosols can result in overestimation of mass concentrations by much as a factor of four based on reported comparisons using woodsmoke on the Dusttrak and the UCB-PATS, a lower-cost light-scattering device (*34*). This is especially a concern if concentrations are used to derive exposure-response functions.

In urban air samples, pollutant mixtures are in a sense “averaged” as they are mixed, attenuating differences due to individual source contributors. At the household-level, aerosols typically originate from far fewer sources, but may have very different aerosol compositions, depending on fuel-use activities. An adjustment factor for the DustTrak (“*k-factor*”) was calculated for each experiment by dividing the filter-based $PM_{2.5}$ concentration by DustTrak concentrations over the same sample period. The effect of aerosol differences on DustTrak response can be observed over the range of *k-factors* in **Table 3.3.1.** In the most extreme case, the simple wick lamp had a *k-factor* indicating an overestimation of 7.5 times, while the chulo adjustment was about half of this. The effect of combustion conditions is also seen when observing across appliances with identical fuel. Adjustment factors for the kerosene stove and kerosene lamp, for example, were different by a factor of three. This is an indication of differences resulting from particle size distribution, as suggested by the TSP/$PM_{2.5}$ ratio, and perhaps EC composition, being much larger for the lamp (See **Section 3.3.2**).

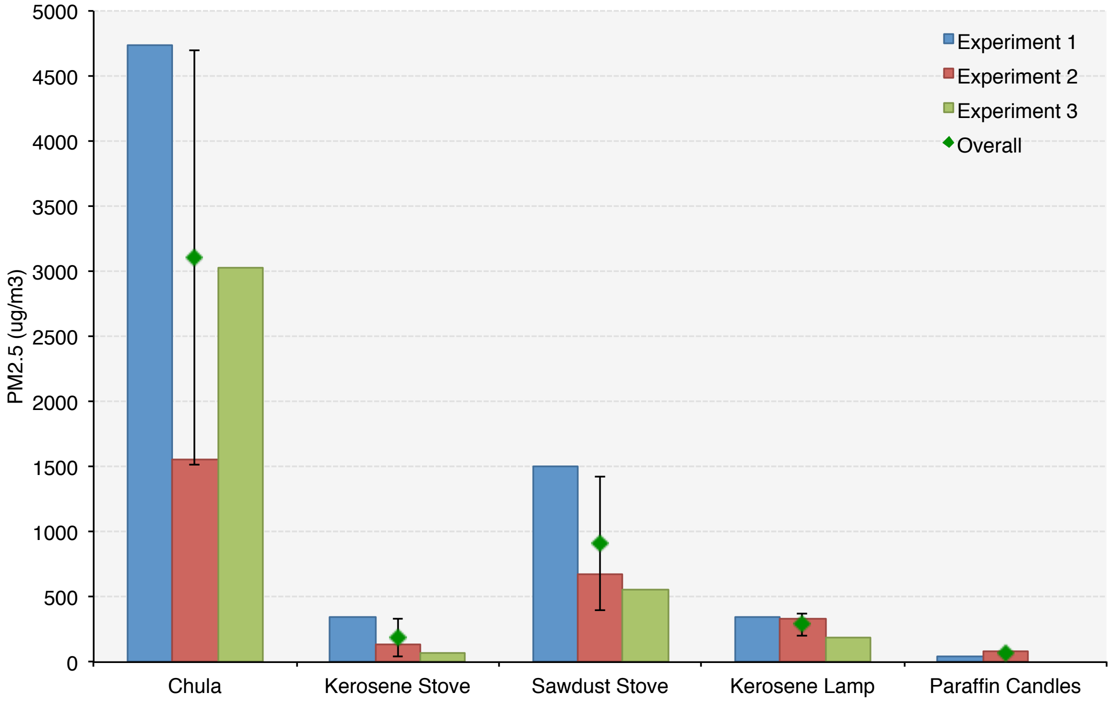


Figure 3.3.1. Room $PM_{2.5}$ concentrations by experiment and combustion device. Average device concentrations are presented as green diamonds with error bars corresponding to the standard deviation, except for the paraffin candle which only had two samples.

3.3.1.2 Carbon Monoxide and CO/PM Relationships

Carbon monoxide concentrations across tested appliances varied by a factor of 40, ranging from below instrument detection limits to levels of potential acute health risk. The single-test CO/PM ratio for the chulo wood stove was 0.15, and within 20% of results obtained from previously published ratios using average kitchen concentration measurements (*2, 5, 35*). The CO/PM ratio for the kerosene stove was 0.07, approximately half the chulo. CO/PM ratios were effectively zero for both kerosene lamps and candles, since CO was less than the instrument limit of detection (0.2 ppm). Results suggest that presence of CO is not an effective proxy for identifying PM from lighting sources, however, high PM concentrations in the absence of CO in indoor environments could be an indication of lighting sources.

3.3.2 Aerosol Carbon: Elemental Carbon & Organic Carbon

Quartz filters were analyzed for total aerosol carbon (TC) and apportioned into elemental (EC) and organic (OC) components. Chemically defined EC is often used interchangeably with optically measured black carbon (BC), which is not measured here. From some pollutant sources, there is little difference between EC and BC defined aerosol concentrations (e.g. kerosene lamps – see **Chapter 2**), however, for consistency, EC measures will be referred to as such in subsequent sections. Although filters were collected in all experiments, only the filters from the first experiment were analyzed for reporting here.

Trends in total aerosol carbon (TC) were approximately parallel to PM mass concentrations (TSP or $PM_{2.5}$), however, the proportion of BC and OC deviated from PM mass trends (**Figure 3.3.2**). EC concentrations were highest during operation of the kerosene lamp, corresponding to concentrations 2.3 and 2.7 times greater than chulo and sawdust stove levels, respectively (**Table 3.3.2**). The lowest concentrations were observed during operation of candles and the kerosene stove.

Aerosol carbon fractions of EC and OC varied over tested devices and deviated in inconsistent with that of PM mass concentrations. Both the paraffin candle and kerosene lamp were nearly pure EC (EC/TC = 1), although, given analytical uncertainty, a small fraction of OC may have been present. High EC/TC ratios from the kerosene lamp are consistent with those from lab experiments reported in **Chapter 2**. The lowest EC fractions, or alternatively the largest OC fractions, were measured from the chulo wood stove. The measured EC/TC ratio of 0.13 is within the range of reported values for other wood-fueled cookstoves in the literature, which range from 0.05 to 0.50 (*32, 33, 36-38*). The observed EC/TC ratio of the kerosene stove (0.40) was slightly lower than summary estimates by Bond et al. of around 0.5-0.6 (*39*), and approximately double those from lab experiments performed by Venkataraman et al. (*38*). Differences in fuel composition and stove designs, which are often not clearly defined, may be contributing to the variability observed in the literature. Considering analysis from other device experiments is pending chemical analysis but not expected to change reported trends.

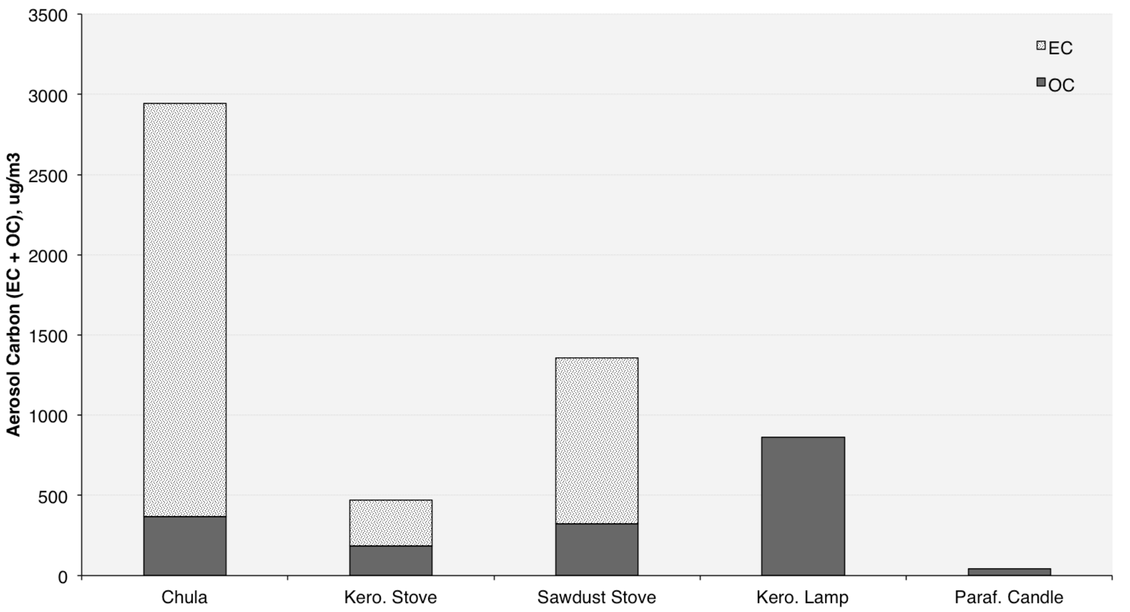


Figure 3.3.2. Total aerosol carbon (TC) concentrations apportioned into the elemental carbon (dark strata) and organic carbon (light strata) components. Each bar corresponds to results from a single experiment performed with the appliance. EC/OC analysis was performed on quartz filters taken from the first experiment of each device.

Table 3.3.2. Total aerosol carbon (TC), elemental (EC) and organic carbon (OC) concentrations, as well as corresponding composition ratios. Values in parentheses correspond to analytical uncertainty[2]. The TC/TSP ratio is the ratio of the total aerosol carbon to total suspended particle concentration from corresponding test periods (TSP values presented in **Table 3.3.1**). Chemical analysis for TC, EC and OC was performed on filters collected from the first experiment of each device.

	EC	**OC**	**TC**	**EC/TC**	**TC/TSP**[1]
	$\mu g/m^3$	*$\mu g/m^3$*	*$\mu g/m^3$*		
Chulo	370 (30)	2573 (230)	2943 (230)	0.13 (0.01)	56%
Kerosene Stove	186 (18)	284 (65)	471 (76)	0.40 (0.04)	104%
Sawdust Stove	322 (23)	1033 (107)	1356 (117)	0.24 (0.02)	110%
Kerosene Lamp	861 (56)	0 (63)	861 (93)	1.00 (0.07)	99%
Paraffin Candle	43 (5)	0 (18)	43 (20)	1.00 (0.12)	38%

[1] *TSP ($\mu g/m^3$) concentrations correspond to the first experiment of each appliance in **Table 3.3.1**, with the exception of the paraffin candle (2nd experiment) as not PAH samples were collected in the first experiment.*

[2] *Analytical uncertainties refer to the uncertainty resulting from the chemical analysis process and do not include environmental or sampling uncertainties*

3.3.3 Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs in the environment can be grouped in two general source categories: those formed from the combustion of organic materials (pyrogenic) and those from residues of non-combusted PAH-containing parent fuels, such as those found in diesel and kerosene (petrogenic) (*16, 19*). Both the fuel composition and combustion conditions (e.g. temperature, oxygen levels, residence time) have been observed to alter pyrogenic PAH formation, affecting emission magnitudes and their relative proportions to one another (*16*).

Characteristics of PAH emissions measured in air and sediments have been leveraged to construct diagnostic markers for semi-quantitatively attributing PAHs in environments to originating sources (e.g. fuel type, formation type) or activities (e.g. automobile, biomass combustion), depending on the measurement context (*16, 21*). The method most commonly found in the literature is use of diagnostic ratios, which are based on relationships between PAH isomers. Others have attempted to consider a more complete view of PAHs in the form of source-specific PAH “fingerprints” (*21*). Hundreds of studies have reported environmental concentrations of PAHs, mostly in the context of outdoor concentrations in urban centers. Several studies report on the emissions of PAHs from a variety of residential sources of combustion in developing countries (*40-44*). Fewer have evaluated exposure concentrations in households (*45-47*) or attempted to apply diagnostic ratios to differentiate source categories.

PAH concentrations were measured using several methods. Environmental concentrations are reported and compared across methods and appliances, when applicable. For each experiment, combined particle and vapor phase concentrations of 14 US EPA priority PAH compounds and retene were measured using XAD-imgregnated quartz fiber filters. Given the time intensive process of chemically analyzing XAD filters, two filter sets per appliance was analyzed (with the exception of the paraffin candle for which only one experiment was conducted with PAH media). A photoionization aerosol monitor was used to provide a continuous measure of particle-bound PAH concentrations. Naphthalene was actively sampled with XAD sorbent tubes.

3.3.3.1 Chemical Measures of PAH

Average PAH concentrations from active sampling instruments are presented in **Table 3.3.3**. Continuous readings from the PAS 2000CE correspond to particle-bound PAHs. Results from each measurement method are discussed greater detail within subsequent sub-sections.

Table 3.3.3. Average PAH concentrations (ng/m^3) based on XAD sorbent tubes, XAD-imgregnated quartz fiber filters and a continuous reading photoionization detector (PAS 2000CE). Values in bold within parentheses correspond to the standard deviation of individual device experiments (n=3).

		XAD Tubes[1]	***Active XAD Filters***			***PAS 2000CE***[5]
Device	**Exp.**	**Naphthalene**	**All**[2]	≤ 3 rings[3]	> 3 rings[4]	Particle, <1um
		(µg/m^3)	*(µg/m^3)*	*(µg/m^3)*	*(µg/m^3)*	*(µg/m^3)*
Chulo Stove	**All**	**15.1 (5.8)**				**0.650 (0.316)**
	1	11.5 (7.0, 16.0)	12.14	9.31	2.84	1.01 (0.29)
	2	11.9 (11.9, 11.9)	3.64	2.35	1.30	0.48 (0.31)
	3	21.8 (21.2, 22.4)				0.46 (0.21)
Kerosene Stove	**All**	**11.3 (1.7)**				**0.07 (0.05)**
	1	9.8 (14.2, 5.3)	2.09*	0.82*	1.27	0.12 (0.30)
	2	13.1 (13.6, 12.7)	2.35	1.76	0.60	0.05 (0.21)
	3	10.9 (11.9, 9.8)				0.04 (0.15)
Sawdust Stove	**All**	**39.8 (8.5)**				**0.60 (0.60)**
	1	30.5 (32.6, 28.3)	38.87*	26.23*	12.64	0.67 (0.49)
	2	42.0 (42.7, 41.3)	13.06	8.58	4.48	0.56 (0.44)
	3	47.0 (46.4, 47.5)				0.58 (0.48)
Kerosene Lamp	**All**	**7.4 (8.5)**				**0.60 (0.27)**
	1	1.6 (1.4, 1.8)	0.19*	0.18*	0.01	0.83 (0.32)
	2	3.5 (3.1, 4.0)	0.35	0.28	0.07	0.68 (0.27)
	3	17.2 (20.3, 14.0)				0.30 (0.28)
Paraffin Candle	**All**	**9.3 (-)**				**0.11 (-)**
	1	ND	ND	ND	ND	0.027 (0.65)
	2	9.3 (9.8, 8.8)	0.24*	0.22*	0.02	0.19 (0.20)

[1] Experimental concentrations correspond to the average of XAD duplicate tubes, values in parentheses correspond (experiment 1, experiment 2)

[2] All: acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indenopyrene, dibenzanthracene, retene

[3] ≤ 3 rings: acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene

[4] > 3 rings: fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indenopyrene, dibenzanthracene, retene

[5] Representative of total particle bound PAHs. Values in parentheses for individual experiments correspond to the standard deviation of continuous measurements.

** Breakthrough for one or more vapor phase PAH exceeded 50% on samples from the first experiment*

ND = No Data

3.3.3.1.1 *Naphthalene*

Average appliance-level naphthalene concentrations ranged from 11 to 44 ug/m^3, corresponding to a maximum difference of a factor of four, approximately (**Figure 3.3.3**). Qualitative trends across appliances were similar to those observed in XAD filter trends, with the sawdust and chulo exhibiting the highest concentrations and the two light sources the lowest.

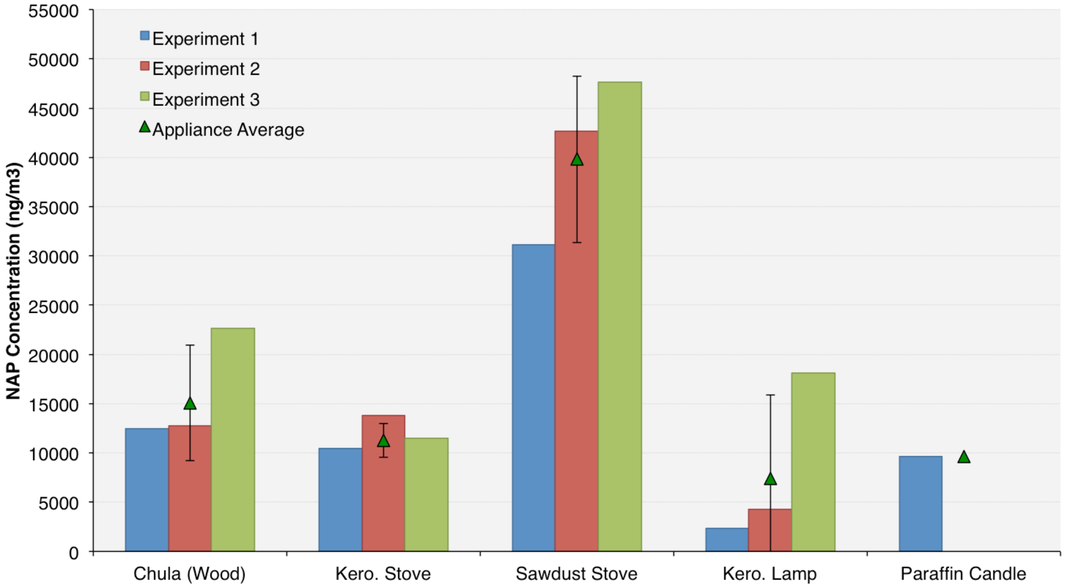


Figure 3.3.3. Naphthalene concentrations (ng/m^3) measured during appliance operation. Individual bars represent the average concentration from each experiment and are the average of two XAD sorbent tubes sampled simultaneously. Appliance-level averages are presented as a green diamonds. Error bars correspond to one standard deviation and presented for appliances with three experiments (excludes paraffin candle).

Naphthalene masses from experimental tubes were 2 to 16 times greater than the average of analytical blanks (30 ng). Unfortunately, no outdoor samples were collected during experiments; however, outdoor ambient naphthalene concentrations have been reported to be between 1-5 ug/m^3 (*48*) and as high as 100 ug/m^3 in Mumbai, India (*49*). One XAD tube from each set of appliance experiments was tested for breakthrough. No breakthrough was detected for any sample based on a back to front threshold ratio of 25%. The agreement between concentrations from duplicate measures was very strong (*r-squared* = 0.92). A similar comparison based on naphthalene masses, as opposed to concentrations, increases the R-squared by less than half a percent. Comparison of duplicate measures is presented in the **Appendix A3.2**.

3.3.3.1.2 *US EPA Priority PAHs & Retene*

Fifteen vapor and particle-bound PAHs were measured from XAD filters. Filters from the first and second experiment are presented, with the exception of the paraffin candle for which there was only a single experiment with PAH measurement. Total concentrations are apportioned into individual PAHs in **Figure 3.3.4**. **Figure 3.3.5** provides an alternative visualization over all tested devices. Devices with lower-concentrations are presented in a companion figure for visual clarity (**Figure 3.3.6**).

Differences in combined PAH concentrations (total) varied by a factor of 200 over the five tested appliances. Looking at individual PAH compounds, the species with the smallest differences across appliances were ACE and FLU, at factors of 30 and 80, respectively. This is substantially larger than the factor of five difference observed across devices for naphthalene (**See 3.3.3.1.1**). The highest concentrations were observed during use of the sawdust and chulo wood stoves, while use of the two lighting sources resulted in the lowest concentrations. Of PAH species measured, no single compound was exclusive to a combustion source.

It is important to note that breakthrough of at least one vapor phase PAH was measured for all devices except the chulo (**Table 3.3.4**). In instances of breakthrough, concentration estimates are likely to be underestimated. Breakthrough may have resulted from several factors: saturation of XAD binding sites, high flow rates reducing sampling efficiency in the case of the kerosene stove and light sources, and a combination of the two factors.

Filter-based PAH mass was dominated by compounds with less than four aromatic rings, which is considered an approximate cutoff for vapor phase-species, although partitioning will fluctuate at 3-4 rings. Both wood-fueled cookstoves showed substantial levels across all 15 measured PAH compounds, while the kerosene lamp and paraffin candles emitted PAH almost exclusively in the vapor phase (**Figure 3.3.7**), despite considerable PM and EC concentrations.

With the exception of the kerosene stove, PAHs below the 3 ring cutoff accounted for over 65% of total PAH mass from filters (**Figure 3.3.7**). Including naphthalene from XAD sorbent tubes would increase this fraction further. Approximately 60% of the PAH mass from the kerosene stove was attributed to PAH with > 3 rings, however, 90% of this mass was attributed to retene, which is typically considered to be a marker for softwood combustion. Excluding retene from analysis leaves only EPA priority PAHs, and yields vapor phase fraction that is more consistent with lighting sources. Cumulative percentage of total PAH sample mass provides an alternative method for illustrating differences in composition across the entire range of measured PAHs (**Figure 3.3.8).** Results better illustrate that devices with higher overall emissions of PAHs generally have a larger proportion of total mass attributed to heavier PAH species.

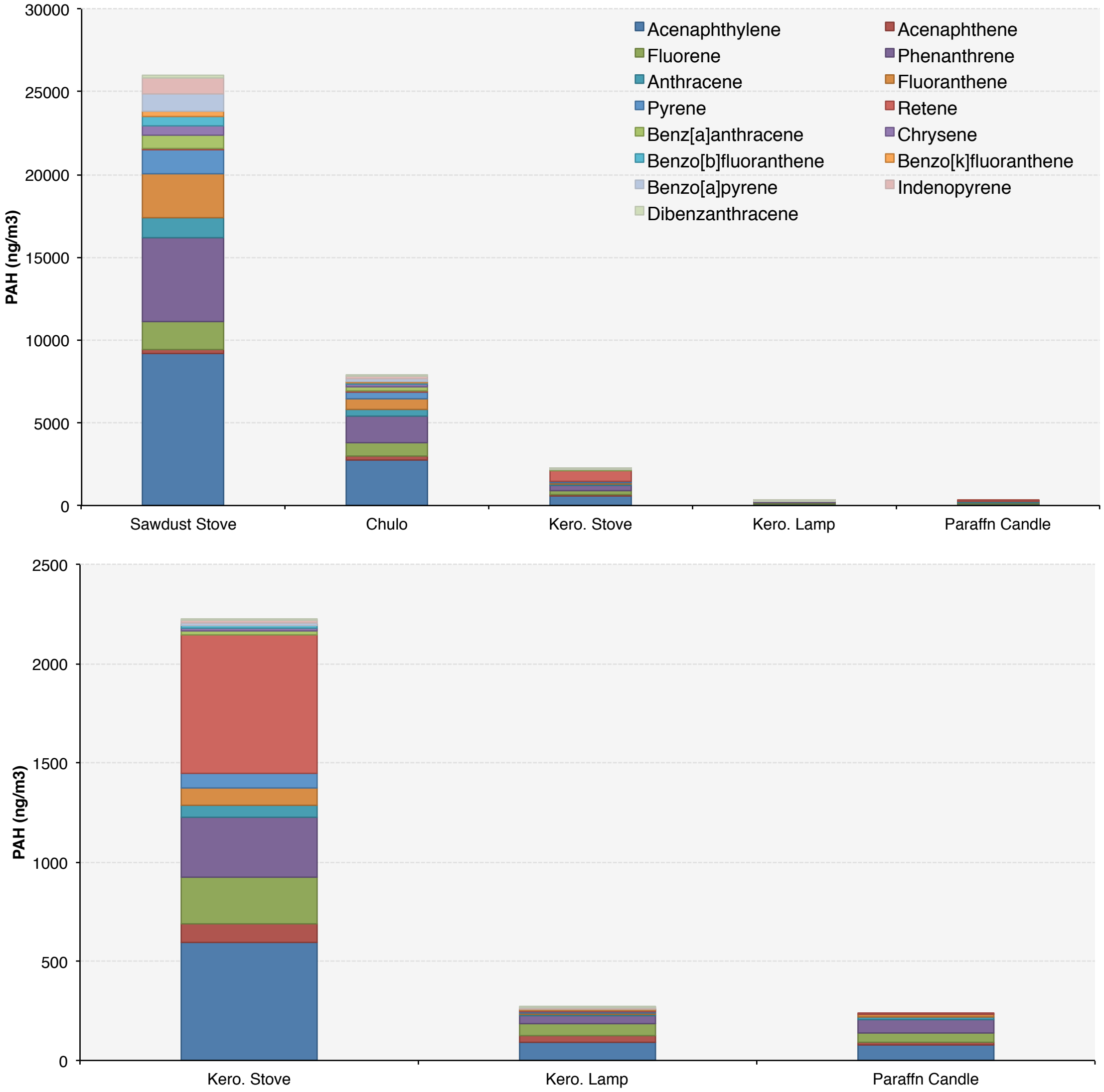


Figure 3.3.4. Appliance specific PAH composition: Combined vapor and particle-bound PAHs with > 2 rings separated into 15 measured compounds over appliance (top panel). For visual clarity, the bottom panel shows the kerosene stove, lamp and paraffin candle. Values represent the average of concentrations measured from the first two experiments for each device (N=2), with the exception of the candle where (N=1). Naphthalene is presented separately (See **Figure 3.3.4**).

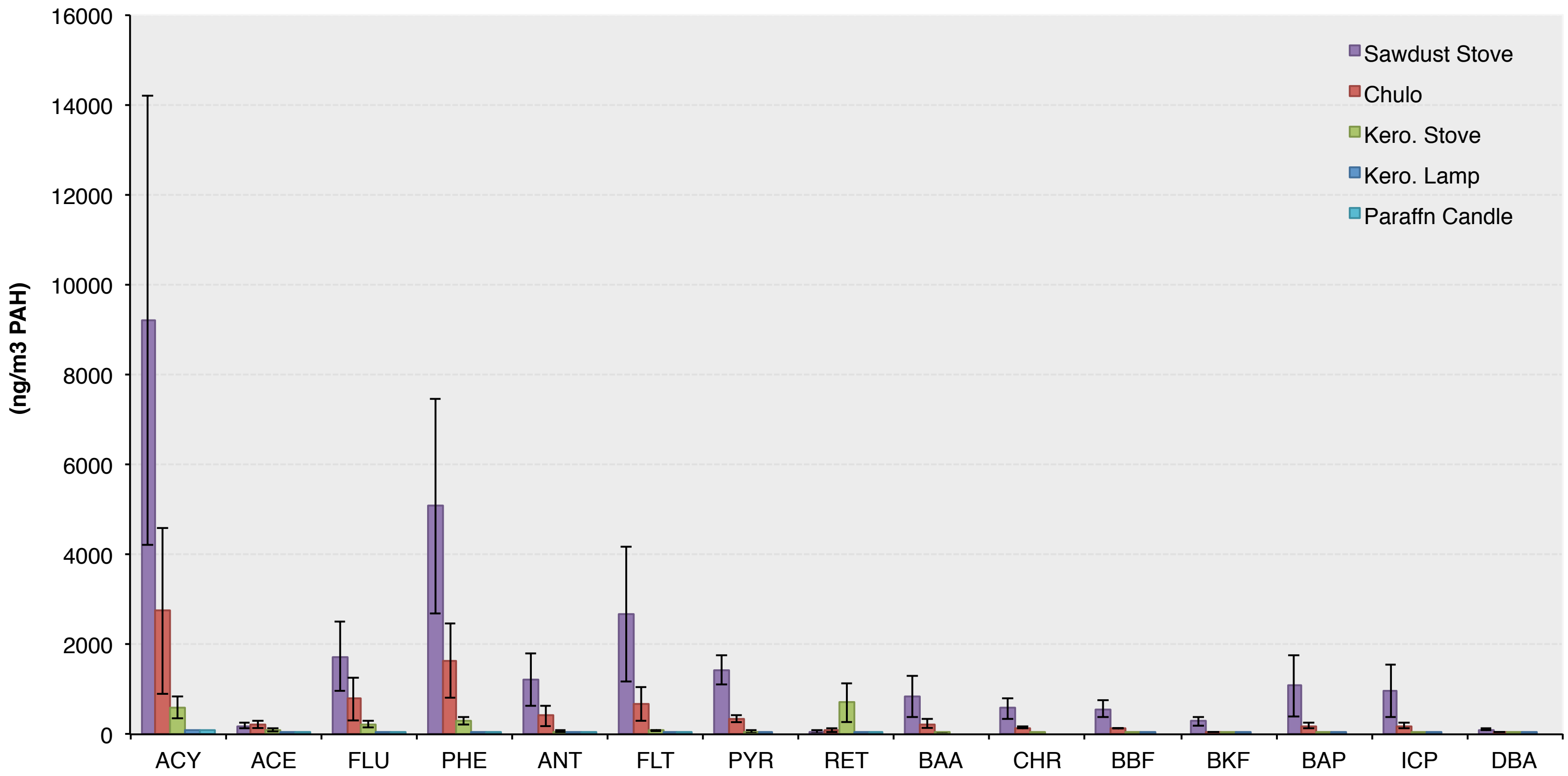


Figure 3.3.5. Comparison of vapor and particle phase PAH concentrations across appliances. Bars corresponds to the average concentrations from two experiments, while ends of the bars correspond to the concentrations of the two experiments. Due to limitations in sample media, only one paraffin candle experiment was conducted with PAH media.

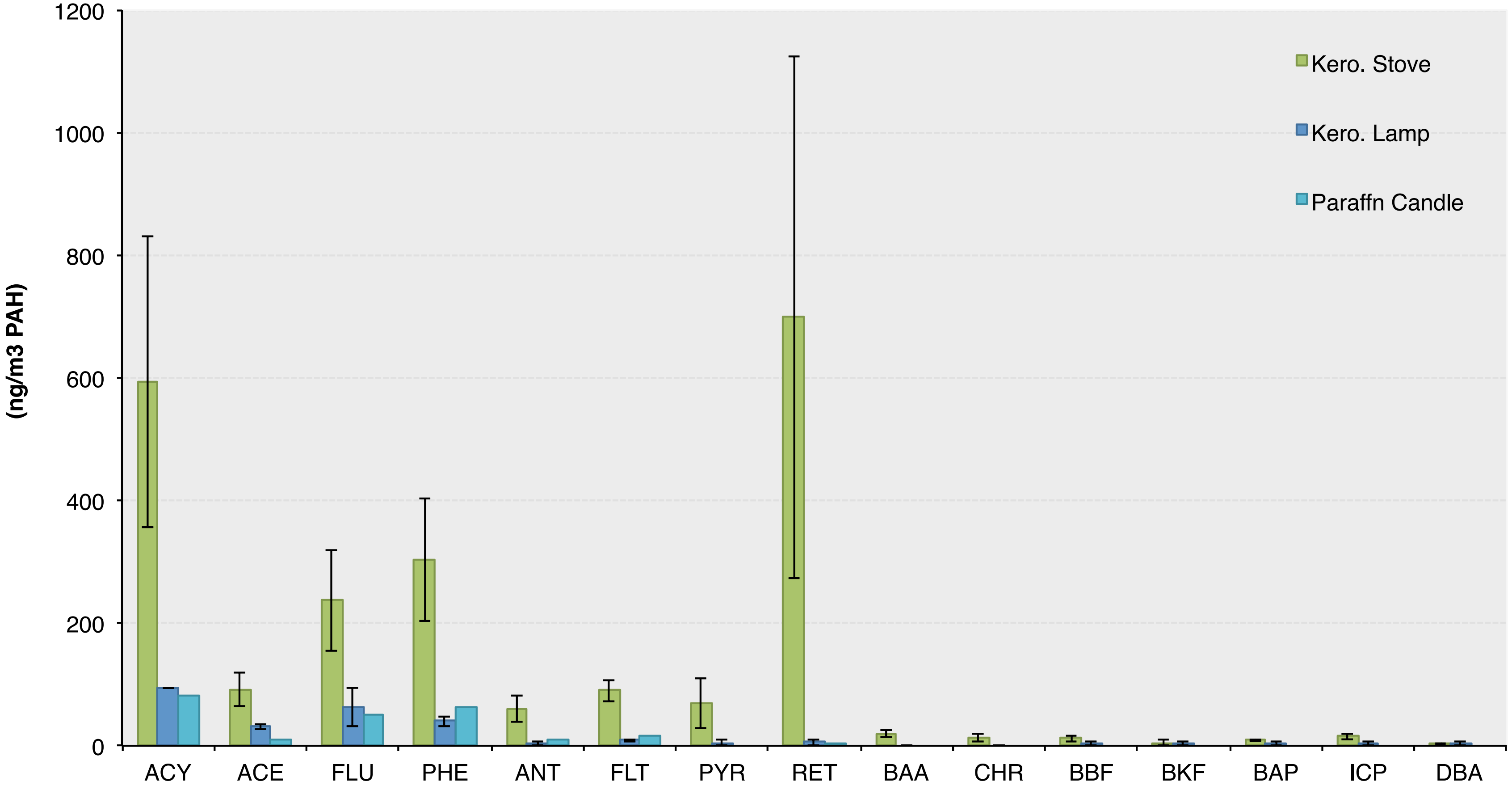


Figure 3.3.6. Comparison of vapor and particle phase PAH concentrations of appliances with lower PAH concentrations in Figure 3.3.5. The bar corresponds to the average concentrations from two experiments, while ends of the bars correspond to the concentrations of the two experiments. Due to limitations in sample media, only one paraffin candle experiment was conducted with PAH media.

Table 3.3.4. Average concentrations (ng/m^3) of 15 PAH measured by actively sampled XAD filters during appliance operation. Values are the average of the first two experiments, with the exception of the paraffin candle. Values in parentheses correspond to the individual values from the first and second experiment. "*%bk*" is the percentage of the back filter mass relative to the front filter. PAHs compounds with breakthrough are indicated with an asterisk (*) and based on results from the first experiment.

		Sawdust Stove		**Chulo Stove**		**Kerosene Stove**		**Kerosene Lamp**		**Paraffin^1 Candle**	
Name	***Abbrv.***	*ng/m^3*	*bk^1*	*ng/m^3*	*bk^1*	*ng/m^3*	*bk^1*	*ng/m^3*	*bk^1*	*ng/m^3*	*%bk^1*
Acenaphthylene	*ACY*	9206 (14207, 4205)	99*	2749 (4597, 901)	26%	594 (357, 832)	224*	95 (94, 95)	64*	>81	305*
Acenaphthene	*ACE*	197 (272, 123)	72*	222 (304, 140)	15%	93 (65, 121)	144*	31 (27, 35)	61*	>10	404*
Fluorene	*FLU*	1721 (2492, 950)	20%	791 (1273, 309)	2%	237 (155, 319)	38%	62 (31, 93)	0%	>51	85*
Phenanthrene	*PHE*	5077 (7466, 2689)	1%	1650 (2485, 815)	0%	303 (203, 402)	2%	40 (31, 49)	0%	64	5%
Anthracene	*ANT*	1205 (1793, 617)	0%	417 (652, 182)	0%	60 (39, 81)	0%	4 (0, 8)	0%	11	0%
Fluoranthene	*FLT*	2664 (4166, 1161)	0%	663 (1035, 290)	0%	90 (72, 108)	0%	9 (7, 11)	0%	18	0%
Pyrene	*PYR*	1436 (1761, 1110)	0%	348 (425, 271)	0%	69 (29, 110)	0%	5 (0, 11)	0%	0	0%
Retene	*RET*	58 (94, 21)	0%	79 (127, 31)	0%	700 (1125, 274)	0%	6 (0, 11)	0%	3	0%
Benz[a]anthracene	*BAA*	834 (1289, 380)	0%	239 (335, 143)	0%	20 (14, 26)	0%	0 (0, 0)	0%	0	0%
Chrysene	*CHR*	575 (817, 332)	0%	141 (164, 117)	0%	13 (6, 20)	0%	0 (0, 0)	0%	0	0%
Benzo[b]fluoranthene	*BBF*	566 (751, 382)	0%	135 (155, 116)	0%	12 (7, 17)	0%	3 (0, 7)	0%	0	0%
Benzo[k]fluoranthene	*BKF*	290 (389, 192)	0%	51 (54, 47)	0%	5 (0, 9)	0%	3 (0, 7)	0%	0	0%
Benzo[a]pyrene	*BAP*	1081 (1766, 397)	0%	182 (249, 114)	0%	9 (10, 8)	0%	4 (0, 8)	0%	0	0%
Indenopyrene	*ICP*	951 (1530, 372)	0%	187 (251, 122)	0%	15 (10, 20)	0%	4 (0, 7)	0%	0	0%
Dibenzanthracene	*DBA*	107 (80, 134)	0%	42 (39, 45)	0%	3 (0, 5)	0%	4 (0, 7)	0%	0	0%
	Total	**9206 (14207, 4205)**		**7894 (12145, 3643)**		**2223 (2093, 2353)**		**270 (190, 350)**		**238 (-)**	

[1] Due to limitations in sample media, only one paraffin candle experiment was conducted with PAH media.

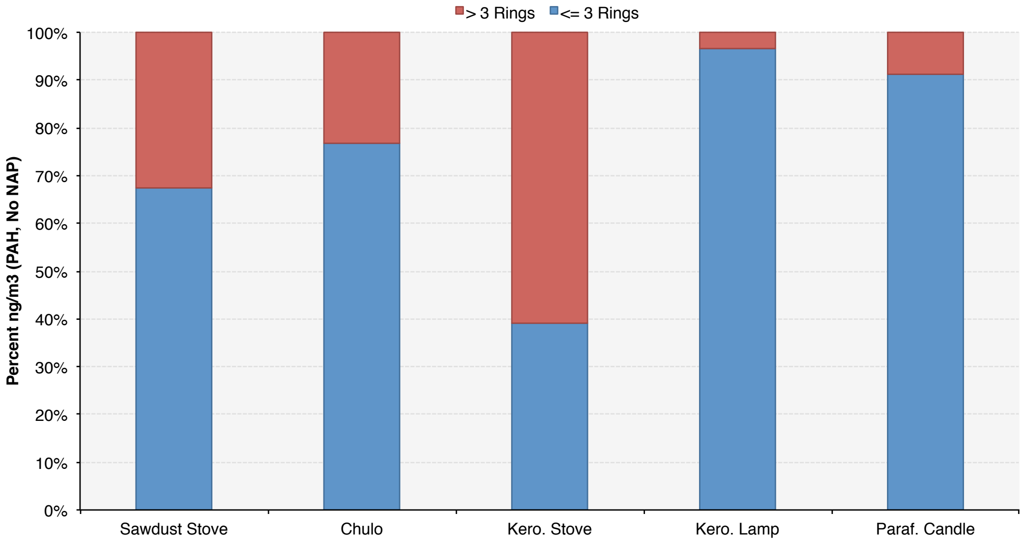


Figure 3.3.7. Percent of total PAH mass attributed to PAHs with > 3 or less than or equal to 3 rings denoting an approximate cutoff for particle-phase dominant and vapor phase dominant PAHs, respectively. Results are based on the average of two experiments per device (with the exception of the candle) and include PAHs listed in **Table 3.3.4**.

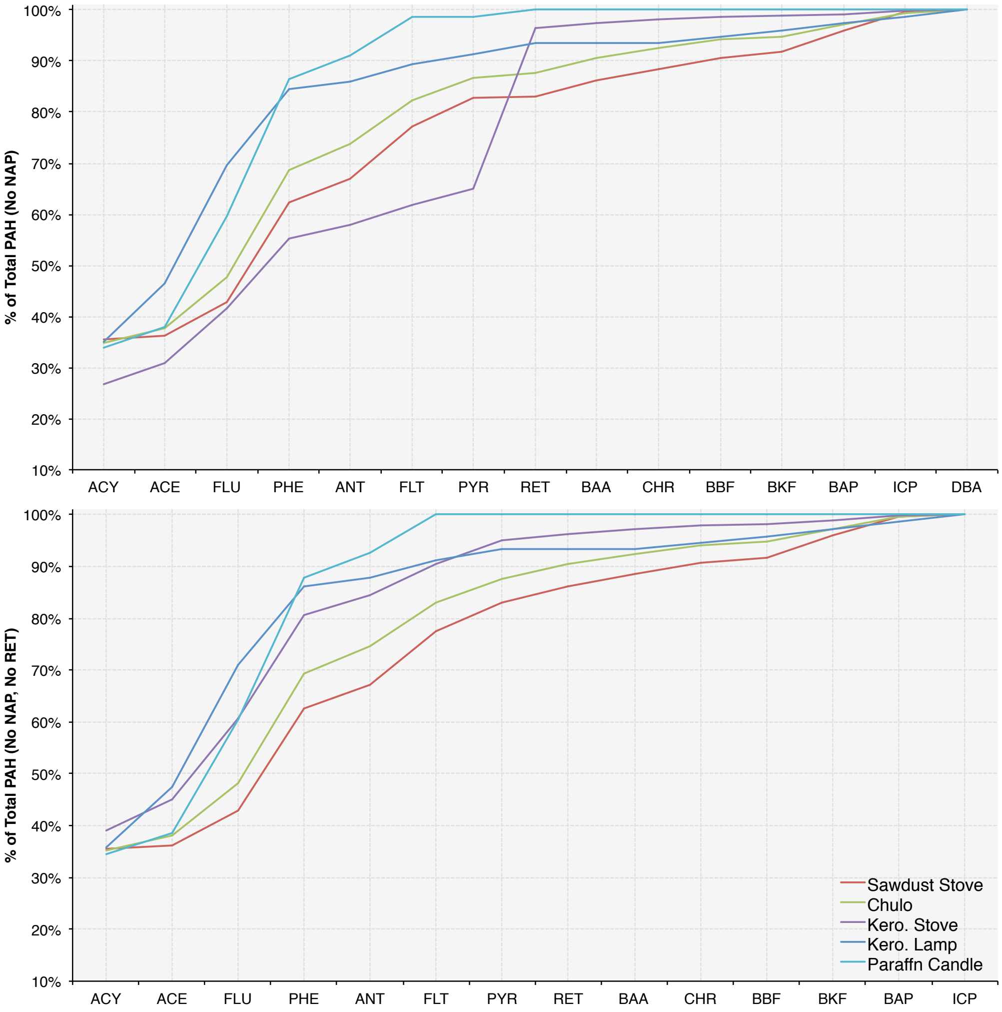


Figure 3.3.8. Cumulative PAH mass percentages based on actively sampled XAD filters. PAHs are arranged along the horizontal axis in order of molecular weight. Retene is removed in the bottom panel to illustrate only US EPA priority PAHs (No naphthalene), but a placeholder is kept for visual comparison between panels. Results are based on the average of XAD filters taken from the first two experiments for each device (N=2), with the exception of the candle (N=1).

3.3.3.1.2.1 Retene

Retene is often applied as marker for softwood combustion in ambient air samples (*50-52*). Although retene was detected during experiments with the chulo (average of two experiment of 79 ng/m^3) and sawdust stove (58 ng/m^3), which both burned pine, the highest concentrations were measured during the use of the kerosene cookstove (700 ng/m^3) (**Table 3.3.4**). Results are consistent with elevated retene levels observed on passive filters deployed on days when the kerosene stove experiments were conducted (results not shown). There was a large reduction between the first and second experiment, however, and more measurements are needed to confirm this finding.

3.3.3.1.2.2 Experiment Correlations

Figure 3.3.9 illustrates PAH trends between the first and second experiment conducted on all devices but the paraffin candle. Differences in the slope away from unity reflect the changes in concentration observed in **Table 3.3.4**, but also illustrate a high degree of correlation between PAH compounds on the same device. These results suggest that changes in the magnitude of total PAH correspond to a proportional shift in other PAH species in the measured set. This proportional scaling may be of use for informing future assessments by allowing for a more limited set of PAH to be quantified, reducing analytical costs and time.

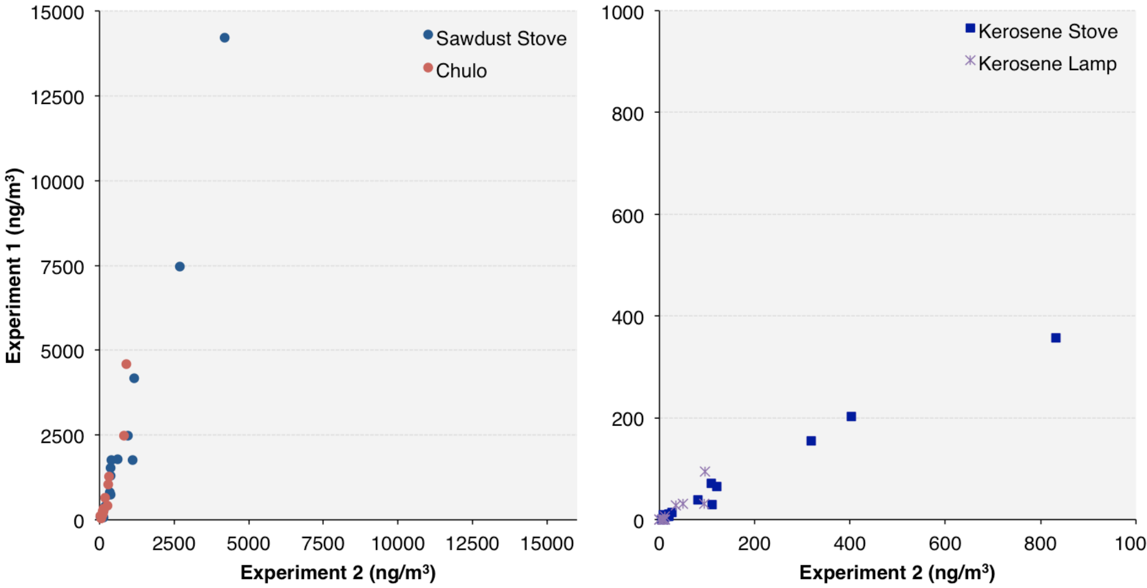


Figure 3.3.9. Comparison of 15 PAH collected from XAD impregnated filters by device. Each point represents an individual PAH compound. Devices are separated for clarity, with higher emitting sources in the left panel and lower emitting source son the right (retene is off scale in the right panel). The paraffin candle is not presented because only on one experiment was conducted with PAH media.

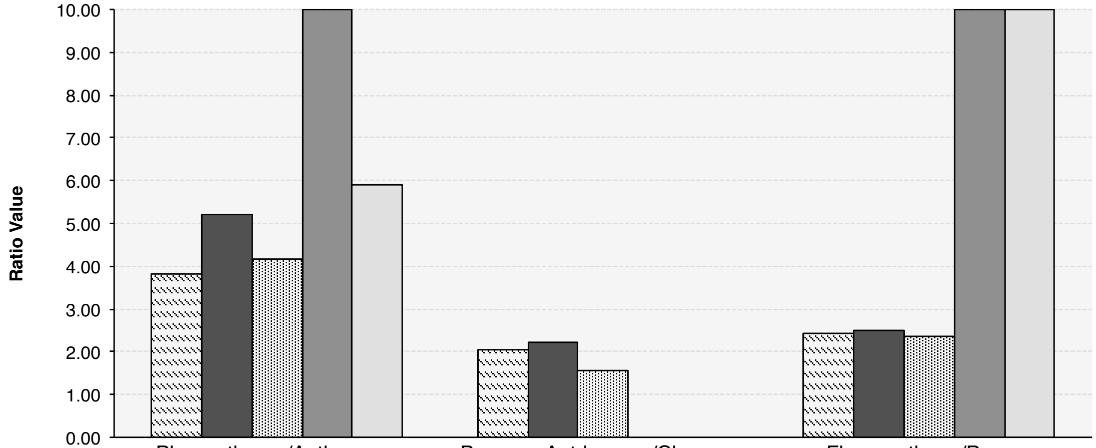
3.3.3.1.2.3 PAH Diagnostic Ratios

Many combustion sources emit qualitatively similar PAH species. That is, the same PAH compounds are often produced during combustion regardless of the combustion conditions (e.g. type of fuel, appliance used to burn the fuel). This is especially true for lower molecular weight PAHs, which typically contribute the majority of total mass. The magnitude of individual species and their relative proportions to one another, however, can be strongly influenced by factors associated with combustion conditions. Fuel composition, such as aromatic content, can directly influence the growth mechanisms of PAH and has been shown to have a positive association with their emissions (*53*). The appliance itself can alter other determinants of PAH formation, such as oxygen levels, temperature and residence time in the flame (*16*). Thus, as suggested by preliminary PAH results, knowing the fuel type alone may not always be sufficient to infer PAH profiles or concentrations (*19*), especially if there is substantial heterogeneity in combustion conditions.

Differences in PAH source emission profiles have been utilized in the aquatic and air pollution literature for several decades to construct source diagnostic ratios (DR). These indicators provide a quantitative threshold for detecting the presence and dominance of specific PAH source by leveraging differences in the relative emissions of PAH species. The resolution at which diagnostic ratios can distinguish between fuel categories and actual combustion devices may vary by context, more specifically the mixture of sources contributing to the sample. As a result, while studies will often reference a ratio value when interpreting results, there is no physical basis justifying use of diagnostic ratios as a universal marker or their utility under all pollutant contexts. Application of diagnostic ratios to-date have been largely limited to analysis of PAHs in soil or ambient urban air of developed countries. There has been substantially less consideration of its use in exposure assessment for either indoor exposure or in the household context.

Components of diagnostic ratios are typically informed by physical properties of PAH compounds, while their associated threshold values for indicating dominance of a source are often based on controlled empirical observations. The most common ratios consist of PAHs of equal mass but differing configuration (isomers) signifying differences in stability during formation or in the environment (*14*). For example, theoretical models and laboratory experiments have indicated that the Phenanthrene/Anthracene (PHE/ANT) ratio is inversely related to combustion temperature (*15, 16*). This physical characteristic has been used to distinguish between petrogenic (PAHs from the parent fuel) and pyrogenic (combustion derived) PAHs in soil samples. In the household context, temperature effects of diagnostic ratio values might be useful for distinguishing activities with different combustion conditions – such as lighting and cooking. A Fluoranthene/(Fluranthene+Pyrene) ratio greater than 0.5 has been used to distinguish between PAH samples dominated by diesel versus gasoline emissions (*17-21*). At a coarser level of source resolution, a Fluoranthene/Pyrene ratio of 0.6 has been used as a cutoff for general vehicular emissions in urban air samples (*16, 19*).

Figure 3.3.10 illustrates results from several PAH diagnostic ratios applied to appliance experiments. The diagnostic ratios presented are not an exhaustive list from the literature, but are a set that could be constructed given available data. Results are considered exploratory but do suggest differences in the ratio values across varying levels of source categorization. In general, however, there are similarities between the two wood-fueled cookstoves, and between the two light sources, regardless of the diagnostic ratio being applied.



	Phenanthrene/Anthracene	Benzo-a-Antrhacene/Chrysene	Fluroanethene/Pyrene
▨Chula (Wood)	3.81	2.04	2.44
■Kero. Stove	5.20	2.21	2.48
▩Sawdust Stove	4.16	1.58	2.37
■Kero. Lamp	10.00		10.00
□Paraf. Candle	5.89		10.00

Figure 3.3.10. Selected PAH diagnostic ratios. No bar indicates that neither PAH species in the ratio were detected. For clarity, when the denominator PAH was below the detection limit but the numerator was detected, the ratio was capped at 10. Results are based on actively sampled PAH filters collected and correspond the average from two experiments on each device (with the exception of the candle).

Results from actively sampled XAD filters were used to construct several diagnostic ratios. Clearly defining any threshold cutoff for a source would require a more robust set of samples, ideally from households. Thus, results are exploratory. The PHE/ANT ratio shows some indication of separation between petroleum-fueled sources and biomass-fueled cookstoves. The PHE/ANT ratios for both light sources are upwards of 20% greater than the biomass cookstoves, especially the kerosene lamp, which is consistent with differences in combustion temperatures. The BAA/CHR ratio was approximately 2.0 for all cooking stoves. Neither BAA nor CHR were detected during experiments with the light sources and thus could not be calculated for **Figures 3.3.10**. Very little Pyrene was detected from either light source, resulting in a very high FLA/PYR ratio relative to cooking fuels.

3.3.3.1.3 PAS 2000CE

Photoionization detectors like the PAS 2000CE provide the only affordable means to continuously monitor PAH concentration in air. Unlike chemical measures of PAHs, photoionization monitors do not speciate, and only provide aggregate measures over all PAH. Based on manufacture specifications, the PAS 2000CE provides a measure of PAHs bound to particles less than one micron in diameter. Ionization readings are converted to PAH concentrations using a non-modifiable response function based on comparison to a manufacture reference PAS, and can only be set during factory calibration. Given the operating principles of the PAS, it would seem likely that some sensitivity to aerosol would exist, since PAHs have varying ionization potentials and combustion sources have varying PAH profiles, as illustrated in previous sections. Cross sensitivity to elemental carbon is also recognized. Despite these sensitivities, there exists relatively little documentation indicating the strength of these effects or information for constructing correction factors. From what can be gleaned from existing literature, correlation between chemical and average PAS readings are generally strong over a single aerosol, however, their concentration magnitudes may disagree by as much as a factor of 25 for diesel tailpipe emissions (27 PAHs, species not specified) or 20 in households with cigarette smokers (18 PAHs including naphthalene) (*54, 55*).

Comparison between average PAS and total PAH mass from filter-based methods are performed in this section. It is important to note that these comparisons are made using the subset of chemically determined PAHs evaluated here and not all PAHs present in the pollutant mixture. Thus, metrics used to compare PAS response to chemical measurements, such as a ratio between PAS and chemically determined PAH used here, would change if a different set of PAH were chemically measured. If we assume that the PAH speciated here are a reasonable representation of unmeasured PAH, trends in the PAS to chemical PAH relationship across measured devices should not be affected.

3.3.3.1.3.1 PAS 2000CE Vs. Chemically Measures of PAHs & EC

PAS response across aerosol sources was evaluated using the ratio of the average PAS reading and total PAH concentration from chemical speciation of 14 USA EPA priority PAHs, PAS/PAH_{14}, and primarily particle bound PAHs, $PAS/PAH_{>3rings}$ (**Table 3.3.5**). PAS and elemental carbon (EC) ratios are also constructed due to the noted cross sensitivity of the PAS 2000CE to EC, and also because soot (EF and BC) formation is intrinsically linked via PAH pre-cursors (*29*).

The PAS/PAH_{14} ratios showed substantial differences across aerosol sources. For cookstoves, PAS readings were lower that $PAHs_{14}$ by a factor of 33, 14 and 9 for the sawdust, kerosene and chulo stoves, respectively. This is indicated by $PAS/PAHs_{14}$ ratio of less than unity. Restricting to particle-bound PAHs (> 3 rings) still yields an underestimate by between 2.6 (chulo) and 11 (sawdust) times. PAS readings of the kerosene lamp were 3.2 times greater than PAH_{14} , but agreed more closely for the paraffin candle ($PAS/PAH_{14} = 0.79$). Little particle bound PAHs were detected from either light source based on chemical measurements, which conflicted with results from the PAS. Resulting PAS/PAH$_{>3rings}$ ratios of light sources considering particle-bound species only indicated overestimation by as much as 70 times (kerosene lamp).

Based on available PAS/EC ratios, there is no visible trend between PAS and EC concentrations. Wood sources have similar PAS/EC response ratios greater than 0.002, while kerosene sources were both lower, at around 0.001. Given the small sample size, however, it's possible that such a difference is within measurement uncertainty. Results from the kerosene lamp do provide an indication of EC cross-sensitivty, since little particle-bound PAHs was measured from XAD filter samples. PAS to EC ratios suggest a cross sensitivity response of roughly 1000:1, that is, a 1 ug increase in PM$_{2.5}$ corresponds to 1 ng increase in PAS response. Quantifying an adjustment factor for EC would require a wider array of tests over various aerosol mixtures.

Table 3.3.5. PAS 2000CE response ratios: Unit change in PAS response per unit change in particle-bound PAHs, 14 US EPA priority PAHs, or elemental carbon (EC). Values in parentheses correspond to ratio values of the first and second experiments.

	PAHs (> 3 Rings)[1]	**PAHs (14)[2]**	**EC[3]**
Chulo	0.38 (0.37, 0.38)	0.11 (0.08, 0.13)	0.0027
Kerosene Stove	0.48 (0.82, 0.14)	0.07 (0.13, 0.02)	0.0007
Sawdust Stove	0.09 (0.05, 0.12)	0.03 (0.02, 0.04)	0.0021
Kerosene Lamp	69 (125, 12)	3.2 (4.4, 2.0)	0.0010
Paraffin Candle	11 (-)	0.79 (-)	0.0043

[1] *PAS (ng/m^3) / XAD-Filter (ng/m^3); FLT, PYR, BAA, CHR, BBF, BKF, BAP, ICP. DBA*
[2] *PAS (ng/m^3) / XAD-Filter (ng/m^3); ACY, ACE, FLU, PHE, ANT FLT, PYR, BAA, CHR, BBF, BKF, BAP, ICP. DBA*
[3] *PAS (ng/m^3) / Filter (ng/ m^3)*

3.3.3.1.3.2 PAS and PM$_{2.5}$

Figure 3.3.11 presents results from a comparison between PAS and PM$_{2.5}$ concentrations across tested aerosol sources. Sources with steeper slopes (more positive) have higher response ratios, indicating a larger increase PAS response per unit increase in PM$_{2.5}$. Overall trends in are consistent with EC/TC trends, but not PAH trends from XAD filters. That is, slopes are steeper (more positive) for devices with greater EC/TC ratios, even when PAH values are actually quite low. The extent to which differences in response are driven by heterogeneity in PAH composition and EC content interaction, however, is not distinguishable given the available samples.

Several studies have demonstrated strong correlations between PM$_{2.5}$ and PAH concentrations from measurements taken during the operation of cookstoves (*43, 45*). Results from this comparison would suggest that PM could be an affective surrogate for particle-bound PAHs, contingent on knowing the PAH composition of the aerosol. Given the considerable variation in PAS/PM$_{2.5}$ response across sources tested here, it may be difficult to accurately adjust PAS readings when multiple aerosol sources are present, unless co-located chemical measurements are available.

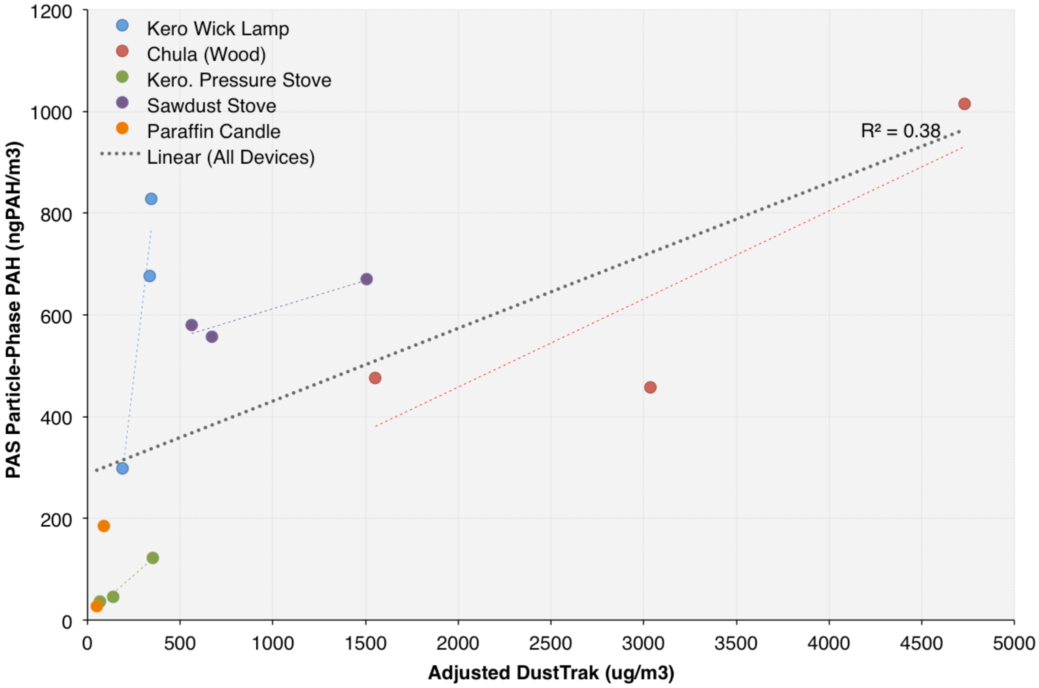


Figure 3.3.11. PAS 2000CE versus $PM_{2.5}$ concentration: Average particle-bound PAHs concentration (ng/m^3) based on unadjusted PAS 2000CE readings versus corresponding average $PM_{2.5}$ concentrations (ug/m^3). Linear best-fit lines are provided by device and over all experiments (black dashed line, R-sq = 0.38)

3.4 Key Findings & Conclusions

Controlled air pollution experiments were performed with selected cooking and lighting devices used in the Kaski District of Nepal. In addition to markers of air pollution commonly used in household air pollution assessments (standard markers) – particulate matter and carbon monoxide – a set of supplement markers were added, consisting of measures of vapor and particle phase PAHs, elemental carbon and organic carbon. Results were used to evaluate whether supplemental markers could provide additional information not reflected by standard pollutants. In the process, I use chemical measurements of PAHs to construct exploratory source diagnostic ratios and provide an indication of the sensitivity of a continuous PAH monitor to various complex mixtures.

3.4.1 Potential Sources of Exposure: Sawdust Stove

In the Kaski region of Nepal, sawdust stoves are commonly used for long duration cooking tasks. The stove utilizes a top loading design in which "packed" sawdust is slowly burned, allowing the device to be operated for long periods without re-fueling. When operated, the sawdust stove yielded average $PM_{2.5}$ concentrations that were approximately one third of the chulo, and 40% lower for CO. The average concentration of 14 US EPA priority PAHs, however, was approximately three times greater than the chulo. Benzo-a-pyrene, which is often used as a marker of carcinogenic potential, was present at concentrations five times greater than the chulo. Sawdust stoves measurements are rare in the literature, as their use is not as prevalent as other biomass stoves and they are rarely the primary cooking device. In the only study identified reporting PAH from sawdust stoves, emission rates of 17 PAHs were 2.2 times greater than the wood stove and 17.5 times greater than a kerosene stove. Environmental concentration results suggest that the sawdust stove has the potential to be a significant source of PAH exposure in households. Determining its importance as an exposure sources, however, will require further validation using personal measurements, in order to account for the behavioral factors that modulates the transition from environmental concentrations to exposure levels. There i

3.4.2 Markers of Pollution

3.4.2.1 PAHs and Aerosol Carbon

Results from a comparison pollutant trends suggest that PAHs and EC do provide additional information not necessarily captured by undifferentiated particulate mass concentrations ($PM_{2.5}$, TSP) and carbon monoxide. **Table 3.4.1** presents rankings of tested appliances using standard markers, as well as the set of supplemental markers, and some derivatives of them. As noted previously, these do not reflect exposure levels, simply area concentrations. Several notable trends emerge from the table. First is that rankings are sensitive to the choice of indicator. For example, standard pollutants markers would unanimously identify the chulo as the leading pollutant source, while PAH metrics would unanimously indicate the sawdust stove. PAH levels expressed per unit of $PM_{2.5}$ ($PAH_{14}/PM_{2.5}$) suggest that pollutant mixtures generated by the sawdust stove are approximately three times more "potent" than the kerosene stove and ten times more than the chulo (**Figure 3.6.3**). The ratio of the highest to lowest concentration also varies from as little as 5.4 (Naphthalene) to as much as 110 (PAH_{14}).

The effectiveness of a pollutant marker will depend on its performance as an instrument for accurately capturing health risks, which is not tested here. What **Table 3.4.1** does illustrate, however, is that PAHs and EC can provide added information that is not captured by undifferentiated PM or CO alone. Results would suggest that is may be possible to use standard markers as further indicators of tested supplemental markers, but contingent upon validating source-specific relationships (e.g. $PAH/PM_{2.5}$ ratios). This "marker to marker" extrapolation, however, may become prone to misclassification error as fuel or device stacking increases; that is, multiple complex mixture sources are contributing to the pollutant sample.

Table 3.4.1. Device rankings over selected markers. Rankings are ordered from highest (1) concentration to lowest concentration (5) using average concentrations from experiments. Fold difference represents the ratio of the average concentration of the highest device, divided by the average concentration of the lowest device. "Samples per Device" is the number of experiments per device available to perform this comparison as not all chemical analyses have been completed.

	Standard Markers			**Supplement Markers**			
	$PM_{2.5}$	TSP	CO	EC	PAH_{14}[1]	$PAH_{14}/PM_{2.5}$[1]	NAP
Samples per Device	*3*	*3*	*3*	*1*	*2*	*2*	*3*
Chulo	**1**	**1**	**1**	2	2	4	2
Kerosene Stove	4	4	3	4	3	2	3
Sawdust Stove	2	3	2	3	**1**	**1**	**1**
Kerosene Lamp	3	2	4	**1**	4	5	5
Paraffin Candle	5	5	4	5	5	3	4
Max/Min Ratio	45	27	44	20	110	29	5

[1] PAH_{14} = *acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indenopyrene, dibenzanthracene*

Improvements in sampling technology and laboratory techniques may provide more opportunities to apply PAHs and aerosol carbon measurements in future household air pollution studies. Linkages between PAHs and immunosuppressive effects mean the PAHs may serve as markers while also being a measure of an active agent. Recent evidence also suggests that EC and BC may also improve risk estimates, relative to undifferentiated particle mass. In a recent meta-analysis using data from urban centers in developed countries, authors found that that risk estimates derived from BC on early mortality were systematically larger and more robust than undifferentiated PM. Estimated life expectancy gains from applying pooled effect estimates in a hypothetical traffic abatement intervention were four to nine times higher using BC than an equivalent reduction in undifferentiated PM (*30*). The authors note that BC itself may not be the active agent, and simply serving as a marker for co-emitted species such as PAHs or other organic species.

3.4.2.2 Retene as a Source Marker

Average retene concentrations during use of the kerosene stove were several times greater than any wood stove tested. These results bring into question retene's use as a unique marker of softwood combustion. Several studies report pollutant emissions of standard pollutants from kerosene stoves (e.g. PM, TSP, CO). However, only two studies have measured PAH emissions (*41, 44*) and neither report retene. Results from several studies, including one on the PAH emissions of coal cookstoves, also report retene from non-softwood combustion sources and have cautioned its use as a source marker (*42, 56*). It is unlikely that the effect was a result of contamination from outside air penetrating indoors. Based on retene concentrations during wood stove operation, the magnitude of the contamination source required for such a high retene signal would have been immediately obvious to test administrators. Retene levels during the second experiment were substantially smaller than levels measured during the first experiment and did not scale proportionally with other PAHs. This is somewhat puzzling and more measurements on kerosene stoves would be needed to confidently rule out the potential of contamination from the stove itself.

3.5 References

1. S. K. Hammond, in *Exposure assessment for epidemiology and hazard control,* S. Rappaport, T. Smith, Eds. (Lewis Publishers, Inc., Chelsea, Michigan, 1991).
2. L. P. Naeher, K. R. Smith, B. P. Leaderer, L. Neufeld, D. T. Mage, Carbon Monoxide As a Tracer for Assessing Exposures to Particulate Matter in Wood and Gas Cookstove Households of Highland Guatemala. *Environmental Science & Technology* **35**, 575-581 (2001).
3. K. R. Smith, J. P. McCracken, M. W. Weber, A. Hubbard, A. Jenny, L. M. Thompson, J. Balmes, A. Diaz, B. Arana, N. Bruce, Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *Lancet* **378**, 1717-1726 (2011).
4. M. Ezzati, B. Mbinda, D. M. Kammen, Comparison of emission and residential exposure from traditional and improved cookstoves in Kenya. *Environmental Science & Technology* **34**, 578-583 (2000).
5. A. Northcross, Z. Chowdhury, J. McCracken, E. Canuz, K. R. Smith, Estimating personal PM2.5 exposures using CO measurements in Guatemalan households cooking with wood fuel. *Journal of Environmental Monitoring* **12**, 873-878 (2009).
6. K. Nadeau, C. McDonald-Hyman, E. M. Noth, B. Pratt, S. K. Hammond, J. Balmes, I. Tager, Ambient air pollution impairs regulatory T-cell function in asthma. *Journal of Allergy and Clinical Immunology* **126**, 845-852.e810 (2010).
7. N. D. Marin, París, S.C., Vélez, V.M., Rojas, C.A., Rojas, M., García, L.F.,, Regulatory T cell frequency and modulation of IFN-gamma and IL-17 in active and latent tuberculosis. *Tuberculosis* **90**, (2010).
8. X. Chen, B. Zhou, M. Li, Q. Deng, X. Wu, X. Le, C. Wu, N. Larmonier, W. Zhang, H. Zhang *et al.*, CD4(+)CD25(+)FoxP3(+) regulatory T cells suppress Mycobacterium tuberculosis immunity in patients with active disease. *Clinical Immunology* **123**, 50-59 (2007).
9. Clement and Associates Inc., "Comparative potency approach for estimating the cancer risk associated with exposure to mixtures of polycyclic aromatic hydrocarbon " (ICF-Clement Associates, Fairfacx, VA, 1988).
10. M. Chu, C. Chen, paper presented at the Pacific Rim Conference, Honolulu, HI, 1984.
11. T. Thorslund, D. Farrer, "Development of relative potency estimates for PAHs and hydrocarbon combustion product fractions compared to benza(a)pyrene and their use in carcinogenic risk assessments," (United States Environmental Protection Agency, 1991).
12. C. Nisbet, P. LaGoy, Toxic equivalency factors (TEFs) for polycyclic aromatic hydrocarbons (PAHs). *Reg. Toxicol. Pharmacol.* **16**, 290-300 (1992).
13. California Environmental Protection Agency, "Technical support document for describing available cancer potentcy factors " *Air toxics hot spots program risk assessment guidelines* (California Environmental Protection Agency, Sacramento, California, 2005).
14. M. B. Yunker, R. W. Macdonald, R. Vingarazan, R. H. Mitchell, D. Goyette, S. Sylvestre, PAHs in the Fraser River basin: a critical appraisal of PAH ratios as

indicators of PAH source and comparison. *Organic Geochemistry* **33**, 489-515 (2002).
15. H. Budzinski, I. Jones, J. Bellocq, C. Piérard, P. Garrigues, Evaluation of sediment contamination by polycyclic aromatic hydrocarbons in the Gironde estuary. *Marine Chemistry* **58**, 85-97 (1997).
16. A. L. C. Lima, J. W. Farrington, C. M. Reddy, Combustion-Derived Polycyclic Aromatic Hydrocarbons in the Environment—A Review. *Environmental Forensics* **6**, 109 - 131 (2005).
17. W. F. Rogge, L. M. Hildemann, M. A. Mazurek, G. R. Cass, B. R. T. Simoneit, Sources of fine organic aerosol. 5. Natural gas home appliances *Environmental Science & Technology* **27**, 2736-2744 (1993).
18. W. F. Rogge, L. M. Hildemann, M. A. Mazurek, G. R. Cass, B. R. T. Simoneit, Sources of fine organic aerosol. 2. Noncatalyst and catalyst equipped automobiles and heavy-duty diesel trucks. *Environmental Science & Technology* **27**, (1993).
19. K. Ravindra, R. Sokhi, R. Vangrieken, Atmospheric polycyclic aromatic hydrocarbons: Source attribution, emission factors and regulation. *Atmospheric Environment* **42**, 2895-2921 (2008).
20. K. Ravindra, L. Bencs, E. Wauters, J. de Hoog, F. Deutsch, E. Roekens, N. Bleux, P. Berghmans, R. Van Grieken, Seasonal and site-specific variation in vapour and aerosol phase PAHs over Flanders (Belgium) and their relation with anthropogenic activities. *Atmospheric Environment* **40**, 771-785 (2006).
21. N. R. Khalil, P. A. Scheff, T. M. Holsen, PAH source fingerprints for coke ovens diesel and gasoline engines, highway tunnels, and wood combustion emissions. *Atmosph. Environ.* **29**, 533-542 (1995).
22. A. K. Pokhrel, M. N. Bates, S. C. Verma, H. S. Joshi, C. T. Sreeramareddy, K. R. Smith, Tuberculosis and Indoor Biomass and Kerosene Use in Nepal: A Case-Control Study. *Environ Health Perspect* **118**, (2010).
23. N. L. Lam, K. R. Smith, A. Gauthier, M. N. Bates, Kerosene: a review of household uses and their hazards in low- and middle-income countries. *Journal of Toxicology and Environmental Health, Parth B: Critical Reviews* **15**, 396-432 (2012).
24. EcoChem Analytics, R. Wasserkort, L. Scherrer, Eds. (EchoChem Analytics, League City, TX, 2005), pp. 46.
25. R. Niessner, The chemical response of the phot-electric aerosol sensor (PAS) to different aerosol systems. *Journal of Aerosol Scince* **17**, 705-714 (1986).
26. J. Wu, T. Tjoa, L. Li, G. Jaimes, R. Delfind, Modeling personal particle-bound polycyclic aromatic hydrocarbon (pb-pah) exposure in human subjects in Southern California. *Environmental Health* **11**, (2012).
27. P. Boparai, J. Lee, T. C. Bond, Revisiting Thermal-Optical Analyses of Carbonaceous Aerosol Using a Physical Model. *Aerosol Sci. Technol.* **42**, 930-948 (2008).
28. NIOSH, "Diesel particulate matter (as Elemental Carbon). NIOSH Manual of Analytical Methods 5040, Issue 3," (2003).
29. H. Richter, J. B. Howards, Formation of polycyclic aromatic hydrocarbons and their growth to soot - a review of chemical reaction pathways. *Progress in Energy and Combustion Science* **26**, 565-608 (2000).

30. N. A. H. Janssen, G. Hoek, M. Simic-lawson, P. Fischer, L. V. Bree, H. Brink, M. Keuken, R. W. Atkinson, H. R. Anderson, B. Brunekreef *et al.*, Review Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM 10 and PM 2 . 5. **119**, 1691-1699 (2011).
31. T. W. Kirchstetter, C. E. Corrigan, T. Novakov, Laboratory and field investigation of the adsorption of gaseous organic compounds onto quartz filters. *Atmos. Environ.* **35**, 1663-1671 (2001).
32. G. Habib, C. Venkataraman, T. C. Bond, J. J. Schauer, Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels. *Environ Sci Technol* **42**, 8829-8834 (2008).
33. C. Venkataraman, A. D. Sagar, G. Habib, N. Lam, K. R. Smith, Indian National Initiative for Advanced Bomass Cookstoves: The benefits of clean combustion. *Energy for Sustainable Development* **14**, 63-72 (2011).
34. C. Armendáriz-Arnez, R. D. Edwards, M. Johnson, I. A. Rosas, F. Espinosa, O. R. Masera, Indoor particle size distributions in homes with open fires and improved Patsari cook stoves. *Atmospheric Environment* **44**, 2881-2886 (2010).
35. N. Bruce, J. McCracken, R. Albalak, M. A. Schei, K. R. Smith, V. Lopez, C. West, Impact of improved stoves, house construction and child location on levels of indoor air pollution exposure in young Guatemalan children. *J Expo Anal Environ Epidemiol* **14**, S26-S33 (2004).
36. M. Johnson, R. Edwards, C. Alatorre Frenk, O. Masera, In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmospheric Environment* **42**, 1206-1222 (2008).
37. C. A. Roden, T. C. Bond, S. Conway, A. B. O. Pinel, Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. *Environ Sci Technol* **40**, 6750-6757 (2006).
38. C. Venkataraman, G. Habib, A. Eiguren-Fernandez, A. H. Miguel, S. K. Friedlander, Residential biofuels in South Asia: Carbonaceous aerosol emissions and climate Impacts. *Science* **307**, 1454-1456 (2005).
39. T. C. Bond, D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo, Z. Klimont, A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* **109**, D14203 (2004).
40. N. T. K. Oanh, D. Albina, L. Ping, X. Wang, Emission of particulate matter and polycyclic aromatic hydrocarbons from select cookstove-fuel systems in Asia. *Biomass and Bioenergy* **28**, 579-590 (2005).
41. N. T. K. Oanh, L. H. Nghiem, Y. L. Phyu, Emissions of polycyclic aromatic hydrocarbons, toxicity and mutagenicity from domestic cooking using sawdust briquettes, wood and kerosene. *Environ Sci Technol* **36**, 833-839 (2002).
42. G. Shen, S. Tao, S. Wei, Y. Zhang, R. Wang, B. Wang, W. Li, H. Shen, Y. Huang, Y. Yang *et al.*, Retene emission from residential solid fuels in China and evaluation of retene as a unique marker for soft wood combustion. *Environmental science & technology* **46**, 4666-4672 (2012).
43. G. Shen, W. Wang, Y. Yang, J. Ding, M. Xue, Y. Min, C. Zhu, H. Shen, W. Li, B. Wang *et al.*, Emissions of PAHs from Indoor Crop Residue Burning in a Typical Rural Stove: Emission Factors, Size Distributions, and Gas−Particle Partitioning. *Environmental Science & Technology* **45**, 1206-1212 (2011).

44. C. Venkataraman, G. Negi, S. Brata Sardar, R. Rastogi, Size distributions of polycyclic aromatic hydrocarbons in aerosol emissions from biofuel combustion. *Journal of Aerosol Science* **33**, 503-518 (2002).
45. M. Titcombe, M. Simcik, Personal and indoor exposure to PM<sub>2.5</sub> and polycyclic aromatic hydrocarbons in the southern highlands of Tanzania: a pilot-scale study. *Environmental Monitoring and Assessment* **180**, 461-476 (2011).
46. J. Ding, J. Zhong, Y. Yang, B. Li, G. Shen, Y. Su, C. Wang, W. Li, H. Shen, B. Wang *et al.*, Occurrence and exposure to polycyclic aromatic hydrocarbons and their derivatives in a rural Chinese home through biomass fuelled cooking. *Environmental Pollution* **169**, 160-166 (2012).
47. J. L. Mumford, C. T. Helmes, X. Lee, J. Seidenberg, S. Nesnow, Mouse skin tumorigenicity studies of indoor coal and wood combustion emissions from homes of residents in Xuan Wei, China with high lung cancer mortality. *Carcinogenesis* **11**, 397-403 (1990).
48. C. Jia, S. Batterman, A critical review of naphthalene sources and exposures relevant to indoor and outdoor air. *Int. J. Environ. Res. Public Health* **7**, 2903-2939 (2010).
49. A. Srivastava, A. E. Joseph, S. Devotta, Volatile organic compounds in ambient air of Mumbai - India. *Atmospheric Environment* **40**, 892-903 (2006).
50. B. Simoneit, Biomass burning - A review of organic tracers for smoke from incomplete combustion. *Applied Geochemsitry* **17**, 129-162 (2002).
51. T. Ramdahl, A molecular marker of wood combustion in ambient air. *Nature*, 580-582 (1983).
52. J. D. McDonald, B. Zielinska, E. M. Fugita, J. C. Saebiel, J. C. Chow, J. G. Watson, Fine particle and gaseous emission rates from residential wood combustion. *Environmental Science & Technology* **34**, 2080-2091 (2000).
53. L. C. Marr, T. W. Kirchstetter, R. A. Harley, A. H. Miguel, S. V. Hering, S. K. Hammond, Characterization of Polycyclic Aromatic Hydrocarbons in Motor Vehicle Fuels and Exhaust Emissions. *Environmental Science & Technology* **33**, 3091-3099 (1999).
54. J. C. Chuang, P. J. Callahan, C. W. Lyu, N. K. Wilson, Polycyclic aromatic hydrocarbon exposures of children in low-income families. *Journal of exposure analysis and environmental epidemiology* **9**, 85-98 (1999).
55. S. Tang, R. Johnson, T. Lanni, W. Webster, T. Tagliaferro, J. Munn, C. Barnes, D. Barnes, K. Newkirk, D. Rivenburgh *et al.*, "Monitoring of PM-bound Polycyclic Aromatic Hydrocarbons from Diesel Vehicles by Photoelectric Aerosol Sensor (PAS)," (New York Department of Environmental Conservation, New York, 2001).
56. D. R. Oros, B. Simoneit, Identification and emission rates of molecular tracers in coal smoke particulate matter. *Fuel* **79**, 515-536 (2000).

4.0 Chapter 4

Kerosene Lighting in Indian Households: Drivers of Demand and Impacts of Use

4.1 Introduction

Households in low- and middle-income countries without access to clean energy provisions often rely on appliances and fuels that are inefficient and have high pollutant emissions. Improvements to the household energy systems to mitigate these emissions are often accompanied by significant co-benefits, ranging in scale from household-level (e.g. health, air quality, time savings) to regional (e.g. outdoor air quality, economic) and global (e.g. climate change) (*1*). While some energy transition may also lead to cross-benefits (e.g. increased CO_2 emissions), the net effect of offsetting highly inefficient fuel impacts is often still favorable. As a result, household energy transitions can play an important and immediate role in helping to improve human welfare through reductions in the global burden of disease (*2*) and environmental impacts (*3-5*).

Achieving adequate household illumination challenges many families in developing countries. An estimated 1.2 billion people (230 million households) lacked access to electricity in 2010 (*6*), while a potentially greater but uncertain number experienced frequent supply interruptions. Several studies have observed lighting to be among the first uses of electricity in newly electrified areas (*7-10*). In the absence of electricity, homes frequently turn to fuel-based lighting, often kerosene-fueled lamps, for illuminating their homes and businesses (*11, 12*). The term "fuel-based lighting" is refers to any combustion-based source of light. In addition to kerosene, other options might include candles, LPG, fuel oil and wood. Many of these traditional kerosene devices are inefficient, however. At equivalent input energy, a typical kerosene lamp will provide 1/500th of the light output (lumens) as an average incandescent bulb (*11, 13*) while converting as much as 10% of the fuel to health and climate damaging particulate matter (PM) (*12*), which has health and climate-change implications. Life cycle efficiencies (lumens/watt) for pico-solar LED lamps, one alternative to kerosene lighting, have been estimated to be 500 times greater than kerosene-fueled lamps (*13*).

A growing body of evidence suggests that kerosene use in households may pose greater risk than previously assumed (*14*). In the lighting literature specifically, acute risks from accidental poisoning and fire-related injuries are perhaps the best documented (*14-17*). Epidemiological studies have associated self-reported use of kerosene for cooking in households with increased risk of respiratory diseases such as pulmonary tuberculosis (*18*) and asthma (*19*), and adverse birth outcomes (*20*). The products of incomplete combustion emitted during lamp operation increase household exposure to health-damaging air pollutants such as fine particulate matter, $PM_{2.5}$ (*21, 22*). This particulate matter is also rich in black carbon (BC), a highly potent short-lived climate warming pollutant (*12, 23*). Estimated global emission rates for kerosene lighting indicate that it is a modest contributor to global PM emissions, but a more substantial contributor to BC (3%) due to the high fraction of BC in emitted aerosol. The BC contribution is greater when looking within the household energy sector, where many sources have high PM emissions but relatively low BC fractions (*23, 24*). It is among a few known BC-rich sources that is both controllable in the near-term and definitively climate warming (*12, 25*).

Initial access to kerosene is often enabled and sustained through government subsidies that are expensive and often inefficient (*26*). Despite the good intent of these programs as redistribution mechanisms to increase access and quality of life of poor households, these inefficiencies can severely reduce program impact (assuming impacts are measured), leading to substantial criticism. In addition to their immediate burden on national budgets, several studies in India have revealed that as much as 30-40% of subsidized kerosene is diverted to non-residential uses (*26, 27*), and provide little benefit to poor rural households where it often serves as a primary lighting fuel (*26*). The same study measured some economic benefit to poor urban households, positing that the effect was a result of its use as a cooking fuel, rather than lighting, in the absence of affordable LPG or biomass. Furthermore, in the case of kerosene, social costs from health and environmental impacts may be substantial but are typically not considered in discussions of kerosene subsidies, or its alternatives. Largely driven by direct economic burdens of subsidies, several countries have moved to limit, re-design, and entirely remove kerosene subsidization (*27, 28*).

Evidence of impacts from kerosene lighting on health (*12, 14, 16*), environment (*11, 12*), and household and national economics (*27*) is growing, but the scale of associated impacts and potential benefits of replacement is less studied. Limited understanding has led to the omission of residential lighting from many of the energy and health assessments that consider impacts of "household energy".

India is an example of a country with widespread use of kerosene as a household energy source and facing many of the associated challenges. National surveys indicate that the use of kerosene as a primary household energy source for cooking and lighting has been on the decline over the last decade; however, such statistics fail to reflect its use as a supplementary fuel for either cooking or lighting. A study of several rural communities, for example, found that 85% of electrified houses surveyed reported continued use of kerosene for light in some capacity (*29*). Subsides on kerosene have existed for over half a century, and fuel prices of subsidized kerosene have changed little in the last decade as global fuel prices and population increase. The fixed per-unit fiscal subsidy on kerosene sold through the subsidy system has changed little in recent decades, leading to a widening gap between the fuel cost and that sales price. This difference, referred to as the under-recovery, observed by government-owned oil companies have therefore increased over time and were estimated at approximately 7 billion USD in 2013 (Summarized within (*30*) and illustrated in **Figure 6.4.1.1**). Responses to mitigate this economic strain have centered on reducing the subsidy and bringing kerosene prices closer to the global market price (*31, 32*)

4.1.1 Study Objectives

This study aims to provide insights into the use of kerosene as a lighting fuel in India, and initial estimates of the national-level impacts from environment, health and economic perspectives. It is the goal that this work begins to fill some of the information gaps associated with residential lighting, while also highlighting new insights that might benefit future research on residential lighting issues and efforts to improve household energy in developing countries. The study evaluates impacts from several dimensions in order to better understand the relationships between them and strengthen future interventions that might be motivated by one or several of these dimensions. As an initial step in developing methodologies, this study focuses on India.

Project aims can be summarized in several points:

- Characterize the consumption and expenditure of kerosene as a primary and secondary lighting fuel in households, and how these trends differ by geography (urban/rural), income and electricity service level.
- Develop a service demand model to estimate future demand for kerosene as a lighting fuel.
- Apply the service demand model to evaluate alternate scenarios effecting electricity connection, electricity reliability and fuel price on future kerosene demand for lighting.
- Evaluate impacts of efforts to modify kerosene demand on kerosene consumption, pollutant emissions, health impacts due to outdoor air pollution and economic welfare in the survey year (2005-6) and in the future under alternate scenarios.

4.2 Methods

4.2.1 Study Overview

An analysis of the India Human Development Survey (IHDS) 2005 (*33*), was performed to quantify national consumption of kerosene used for light and characteristics associated with users across heterogeneous household groups differing by urban/rural status, expenditure and electricity service level. Although kerosene and fuel-based lighting issues are not specific to India, it was selected as the focus of this study, due to the availability of large-scale household consumption surveys with energy characteristics and a its large population of kerosene users. Survey results were used to estimate future demand within a service demand model, an extension of the widely used energy system integrated assessment model MESSAGE (*34*), and explore the effects of mechanisms influencing fuel price (financial access), electricity connection and electricity supply reliability (kerosene dependence), on future consumption of kerosene for lighting. I then evaluate the impact of consumption on selected health, environmental and economic outcomes. Environmental and health impacts from outdoor primary $PM_{2.5}$ are estimated using the GAINS model (*35*). **Figure 4.2.1** presents a schematic of the study design and workflow.

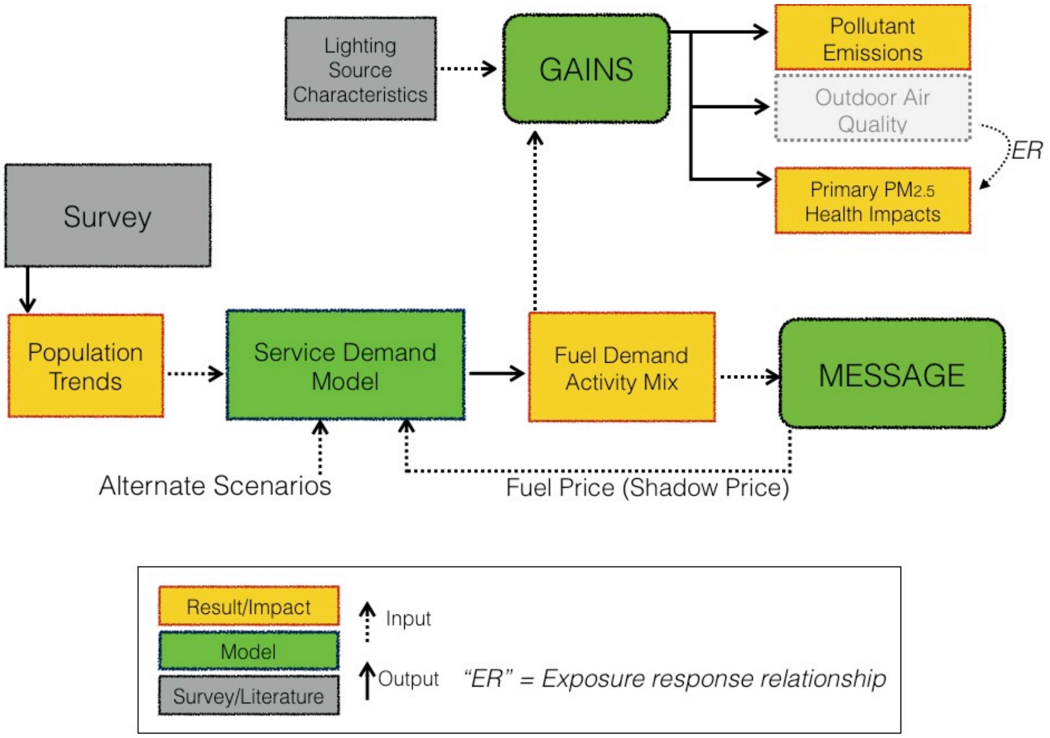


Figure 4.2.1. Study design schematic and workflow. Kerosene lighting trends are derived from the analysis of a national survey. Trends are used to inform a service demand model from which alternate scenarios (e.g. universal electricity connection by 2030) can be tested. The service model provides estimates of kerosene demand for lighting which is linked to MESSAGE (IIASA, Laxenburg, Austria) in order to account for changes global fuel price over time. The GAINS model (IIASA, Laxenburg, Austria)

is used to evaluate pollutant emissions, outdoor air quality and resulting impacts due to primary outdoor $PM_{2.5}$ on adult mortality using an exposure response relationship (*ER*).

4.2.2 Survey and Base Year Analysis

IHDS measures expenditure and quantity of kerosene consumed in the previous 30 days, as well as the activity for which it is mainly used, including combination use and no use. Information on consumption and activity is collected regardless of kerosene's position in the household energy hierarchy (e.g. primary, secondary etc.). If combination use was reported, the amount used for lighting was estimated from observed trends among those reporting lighting as their main use, accounting for household expenditure and electricity service levels. Combination use was assumed to be a mix of cooking and lighting activities, heating being negligible. To facilitate analysis, the population was disaggregated into thirteen groups across three hierarchical levels: geographic sector (urban or rural), total household expenditure ($/person-year) and electricity service level (no electricity, <16 hrs/day, >16 hrs/day). Further description of IHDS and population grouping (**Section 6.4.2.1**) and methods for defining households as primary or secondary users of kerosene (**Section 6.4.2.2**) are available in the appendix.

4.2.3 Alternate Future Scenarios and Kerosene Demand

Alternate scenarios were developed to explore the effect of kerosene price, electricity connection and service reliability on population demand of kerosene for lighting, and associated impacts of consumption. Demand and selected impacts are evaluated in the base year (2005), 2020 and 2030. Fuel demand in the future under all scenarios is adjusted for changes in population, household income, fuel price, and their associated feedbacks, informed by methods developed for the Global Energy Assessment (*36, 37*). Alternate scenarios are described briefly in **Table 4.2.1**, and described in detail along with methods for future demand estimates and dynamics within the appendix (**Sections 6.4.2.3, 6.4.2.4**). A replacement scenario (*Solar*) assumes that kerosene-based lighting is supplanted with reliable technology independent of the grid with full replacement by 2030. For deriving cost control estimates, I assume that the technologies being implemented is pico-solar LED lamps equivalent to those approved under the Lighting Global Minimum Quality Standards (*25, 38*).

Table 4.2.1. Alternate scenario descriptions used to explore effects on future kerosene demand for lighting

Scenario Name	Abbr.	Scenario Description
1. Baseline	*Baseline*	No measures are taken to increase electricity coverage or improve supply beyond changes associated with growing household income.
Alternate Scenario: Reliance		
2. Universal Connection	*UC*	Complete electricity connection coverage by 2030, no additional efforts to improve supply
3. UC + Supply Reliability	*UCS*	UC scenario and all houses have >16 hrs of supply per day by 2030
4. Interim Replacement Technology	*Solar*	All kerosene lighting demand replaced by household pico-solar lamps by 2030
Alternate Scenario: Access		
5. Subsidy Phase-out	*SPO*	All residential kerosene at market prices by 2030
6. Open Subsidy	*FS*	All residential kerosene at subsidy price after base year (2005)

4.2.4 Impacts

Evidence in the peer-reviewed literature on the risks of residential kerosene lighting or benefits of replacement is relatively limited. As a result, few efforts have quantified the magnitude of potential impacts of kerosene lighting or its replacement from any dimension. As a first step, existing evidence from the peer-reviewed literature is used to perform an exploratory examination to quantify a subset of environmental, health and economic consequences of kerosene-based lighting in India, and at the same time the potential opportunities of replacement. All impacts are evaluated in the base year (2005), and for some outcomes in 2020 and 2030 under alternate scenarios. When possible, I separate impacts by contributions from primary and secondary use. More detailed methodologies for evaluating impact are provided in in the appendix (**6.4.2.5**).

4.2.4.1 Pollutant Emissions & Health Impacts from Outdoor Primary $PM_{2.5}$

Emissions of selected pollutant species from kerosene lighting and their subsequent impacts on early mortality from exposure to outdoor primary $PM_{2.5}$ were evaluated using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, developed by IIASA (*35, 39*). Estimates of kerosene consumption for lighting from described in this study were combined with device stock estimates and emission factors to add domestic lighting as an activity within GAINS inventories for South Asia (**Section 6.4.2.4.2**). Ambient concentrations of primary $PM_{2.5}$ are estimated by GAINS using a source-receptor relationship derived from the TM5 model (*40*). Concentrations are then combined with exposure-response relationships to estimate the years of life life (YLL) due to early mortality among adults above 30 years (*39, 41*). The GAINS model quantifies for different emission scenarios premature mortality that can be attributed to long-term exposure to $PM_{2.5}$, following the exposure response outcomes of the American Cancer Society cohort study by Pope et al. 2002 (*42*) and its re-analysis (*43*). This methodology uses an exposure response described in detail within Amann et al. (2011) (*44*). Primary $PM_{2.5}$ control costs are calculated assuming pico-solar lighting technologies and methods describe din detail within the Appendix (**Section 6.4.2.5.1**).

4.2.4.2 Kerosene Subsidy for Lighting

The economic impact of subsidizing kerosene for lighting is estimated by calculating the associated deadweight loss (DWL) in the base year. Deadweight loss is a measure of economic inefficiency resulting from an imposed change in the price of a commodity, away from its natural equilibrium price. In practice, fuel subsidies reduce the price observed by the consumer, allowing for greater consumption than would occur if the household were faced with the true market price (zero subsidy). For comparison, DWL is compared to the social cost of externalities associated with CO_2 and black carbon emissions on climate. Methods for evaluating DWL and the social cost of carbon are provided in **Section 6.4.2.5.3**.

4.3 Results & Discussion

4.3.1 Base Year Consumption and Fuel Use Characteristics

4.3.1.1 Kerosene End-Use Activity

Table 4.3.1 presents kerosene activity prevalence among the entire population of Indian households and only households using kerosene. Residential use of kerosene was reported by over three quarters of households (79%) in 2005. Approximately 20% of kerosene users reported cooking as the main use of kerosene, and only 3% reported that their kerosene use was for mainly heating, which is assumed to be for space heating. The majority of kerosene activity was attributed to lighting (64%). When visualized using spine plots, several interesting trends emerge (**Figure 4.3.1**); corresponding values are presented in **Table 6.4.3.1**. The use of kerosene reported for any lighting decreases with growing electricity supply level. Among the non-electrified, the percentage of households using kerosene for lighting increases as total expenditure grows, but decreases when households are electrified but have approximately equal service level. A combination of kerosene activities was reported by 14% of user households. Based on the low prevalence of space heating, it is assumed that lighting and cooking dominate combination use.

Considering households relying on kerosene as a secondary source of lighting approximately doubles the number of households using kerosene. An estimated 33% of households used kerosene as a primary lighting fuel. This is slightly higher than the National Sample Survey Organization (NSSO) estimate of 25% taken during a similar time period (*45, 46*). Adding households with connections to electricity, but still reporting kerosene as a lighting fuel increases the user households to 61% (**Table 4.3.1**).

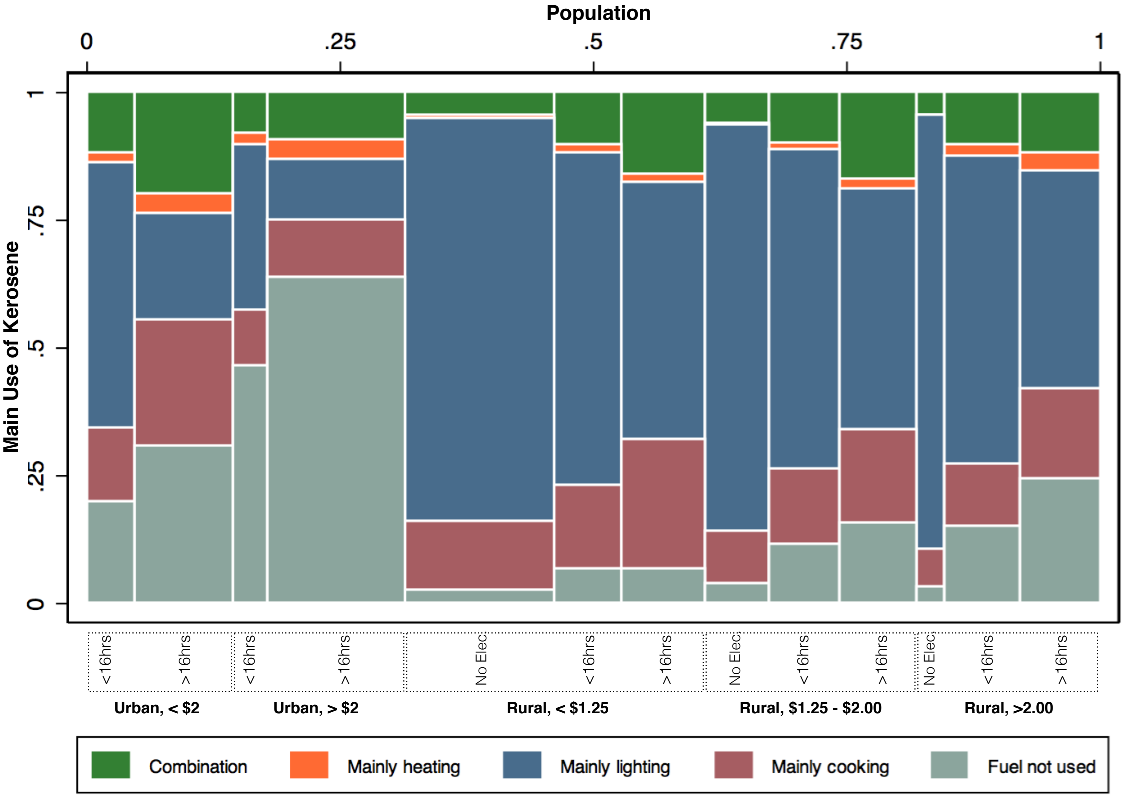


Figure 4.3.1. Main uses of kerosene by electricity service groups, within daily household per-capita expenditure and urban/rural groups. The y-axis corresponds to the total percentage of users within the electricity service sub-group and their reported main use of kerosene. The secondary x-axis (top) corresponds to the percentage each electricity sub-group composes of the full population

Table 4.3.1. Self-reported use of kerosene by activity for all households and among kerosene using households based on IHDS 2005. Values in parentheses represent survey-weighted standard errors.

	All Households	Kerosene Using Households
	(%)	*(%)*
Not Used for Any Activity	21.0 (0.3)	(-)
Mainly Cooking	15.6 (0.3)	19.8 (0.3)
Mainly Lighting	50.4 (0.4)	63.8 (0.5)
Mainly Heating	2.2 (0.1)	2.7 (0.2)
Combination of Activities[1]	10.8 (0.3)	13.7 (0.3)
Total	100 (-)	100 (-)

[1] Assumed to be dominated by cooking and lighting

4.3.1.2 Household Kerosene Consumption

Kerosene consumption for residential lighting considering primary and secondary users was estimated at 4670 Gg. Based on upper and lower 95% confidence intervals of survey estimates (percent of kerosene lighting users, average consumption) yields a 95% confidence bound of 4300 and 5100 Gg, respectively. The central estimate corresponds to approximately 70% of reported residential kerosene in 2005. Rural households accounted for approximately 70% of total residential consumption (5000 Gg) and eighty percent (3840 Gg) of all kerosene consumed for lighting. Across activities, consumption in urban areas was roughly split between cooking (420 Gg, 51%) and lighting: (350 Gg, 43%). In rural areas, lighting constituted 80% (3840 Gg) of residential kerosene use, the remainder going largely to cooking (920 Gg, 19%). Heating activities constituted 2% (160 Gg) of total reported residential kerosene and 1% (60 Gg) and 5% (100 Gg) of kerosene used in rural and urban households, respectively. Total residential kerosene demand estimates agreed to within 10% with results from an analysis of the NSSO 61st round 2004-5 metadata (*45, 46*), a separate nationally representative expenditure survey which measures kerosene consumption but provides less resolution to apportion end-use activities. A comparison of the two survey is presented is presented in the appendix (**Section 6.4.3.2.1**).

4.3.1.2.1 Primary and Secondary Consumption for Lighting

Electrified households often turn to kerosene and other fuel-based light sources during periods of electricity supply interruption (*11, 27, 29*). The extent that secondary usage factors into total demand, however, is less understood. Understanding the extent of secondary demand may be important for targeting and planning future interventions that address lighting and perhaps other household energy issues.

Demand by primary user households constituted 1690 Gg (36%) of all kerosene used for lighting in 2005. From **Chapter 2**, the bottom-up estimate of primary user household consumption based on NSSO survey results was estimated at 1500 Gg for the same year. Secondary user households accounted for the majority of kerosene consumed for residential lighting (2980 Gg, 65%) in 2005. In rural areas, sixty percent (2270 Gg) of lighting kerosene was used by electrified homes, increasing to 85% (710 Gg) in urban areas, where electricity connection rates exceeded 90%. **Table 4.3.2** presents estimated lighting consumption disaggregated by geographic sector and electricity service level.

Table 4.3.2. Residential kerosene consumption for lighting (Gg) in 2005 by electricity service level category. Values in parentheses correspond to the upper and lower 95% CI intervals based on survey-based standard errors.

	Rural	Urban	Total
No Electricity	1570 (1480,1660)	110 (90,140)	1690 (1570,1800)
< 16hrs/day	1230 (1140,1330)	250 (230,270)	1480 (1370,1600)
> 16hrs/day	1040 (890,1200)	460 (420,500)	1500 (1310,1700)
Total	3840 (3500,4190)	820 (750,910)	4670 (4250,5110)

Although non-electrified households consume a large fraction of lighting kerosene, its use as a secondary lighting source among electrified households constitutes the majority of demand, and such use continues even into relatively high service levels (**Figure 4.3.2)**. Results suggest that in addition to issues of reliability, a meaningful amount of secondary kerosene consumption may be filling illumination demands not fulfilled by electricity alone. Previous studies have indicated that kerosene may continue to be used after connection for a variety of tasks, such as mobile light sources or for light in areas of the house where electrical wiring is not available. Results here suggest that these latent demand may be a non-trivial fraction of total kerosene demand for light, although it is unclear what fraction of secondary demand it encompasses.

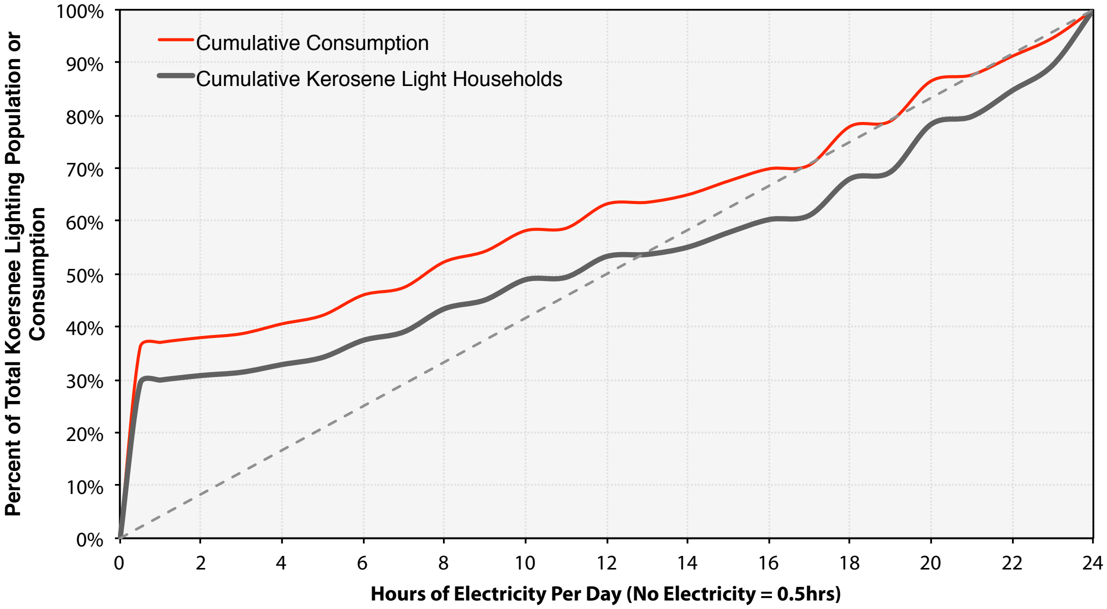


Figure 4.3.2. Cumulative kerosene lighting users and consumption percentages over reported hours of electricity service. The y-axis corresponds to total consumption or total kerosene lighting users. "No electricity" is offset from zero for presentation purposes. The dashed grey line represents the 1:1 relationship.

4.3.1.2.2 Household and Per-Capita Consumption for Lighting

Annual per-capita kerosene consumption for lighting among user households averaged 9.3 liters (9.1, 9.5), or 43 liters per household (42, 44). Applying average fuel and lumen efficiencies of kerosene devices yields daily service levels of approximately 7-8 hours of light per day, or 200 lumen-hours – approximately equivalent to two lamps or lanterns operating daily for 3-4 hours. **Figure 4.3.3** illustrates trends in rural lighting consumption over per-capita expenditure across three electricity service levels. A similar trend is observed for urban electricity supply groups (**Figure 6.4.3.2**). The observed trend is approximately lognormal, with consumption increasing with expenditure and approaching saturation above $2.00/person-day, approximately. The difference in consumption rates and saturation across service levels is suggestive of a modifying effect of electricity service on kerosene consumption. Best fit lines in **Figure 4.3.3** show that non-electrified households consume more kerosene for light than electrified homes with a similar expenditure - although there is significant overlap below $1.00/person-day. Between the two electrified groups, there is some indication of difference above $2.00/person-day, but significant overlap below this. Mean consumption estimates (**Table 6.4.3.2)** and results from regression of kerosene consumption on group characteristics (**6.4.3.2.2)** are consistent with trends observed in figures.

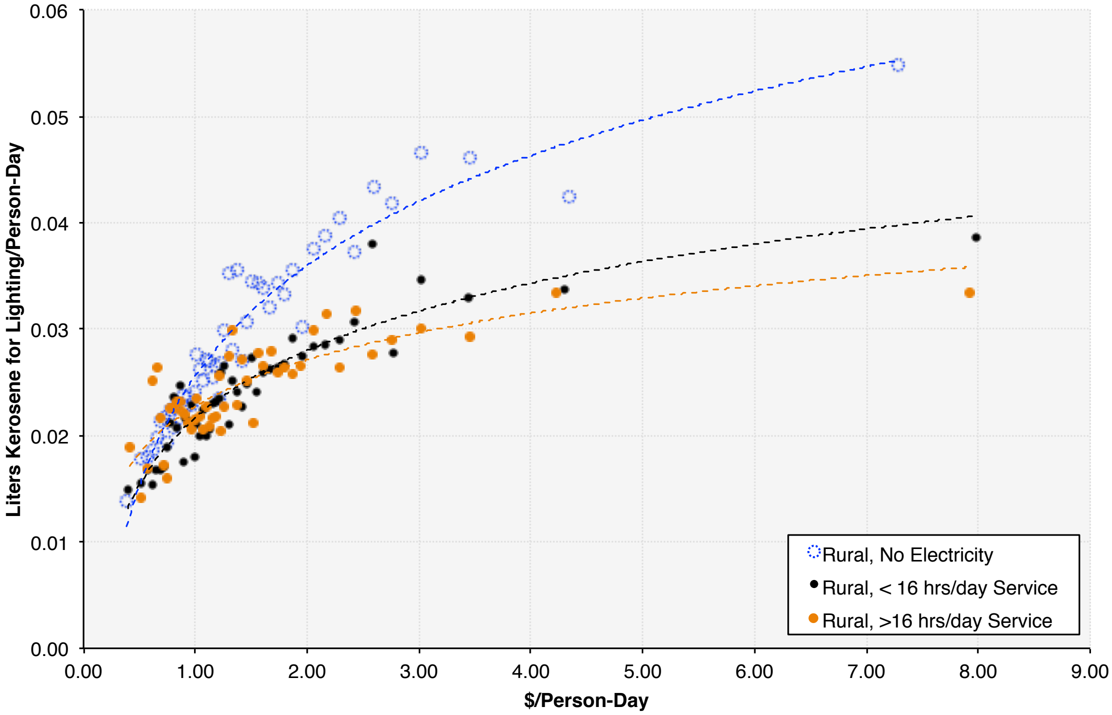


Figure 4.3.3 Rural kerosene consumption for lighting (liters/person-day) versus total household expenditure ($/person-day) among users. Values are compressed into 50 groups for visual clarity and dashed lines represent the line of best-fit. **No Electricity**: $y = 0.0149 ln(x)+0.0256$, $r\text{-}sq = 0.93$; **< 16 hrs/day**: $y = 0.0091 ln(x)+0.0217$, $r\text{-}sq = 0.86$; **> 16 hrs/day**: $y = 0.0063 ln(x)+0.0227$, $r\text{-}sq = 0.67$.

4.3.1.2.3 Lighting Services

Lighting service based on reported consumption is estimated in both *light-hrs* and *lumen-hrs* (**Table 6.4.3.3**) following parameters described in the methods (**Section 6.4.2.4.2**). Resulting trends in service at the expenditure group level are reversed. This is a result of higher quality and more expensive lighting devices (e.g. glass lamps, pressurized mantle lamps) having higher fuel consumption rates, thus yielding fewer hours of light but producing a greater quantity of light output (lumens), relative to the basic simple lighting devices. Combining results on service level and expenditure (**Section 6.4.3.3**) suggests that higher income groups pay the most per hour of light service, but the least per lumen-hour of service (**Table 6.4.3.3.5**). Conversely, the poorest households pay the least per hour of light, but the most on a lumen basis. The choice of metric has no effect on fuel consumption estimates but has implications for interpreting a household's willingness to pay for replacement technologies. For example, results might suggest that in designing solar lighting systems, wealthier household might value the quantity of light, while poor households who already have very poor quality light might value the ability to extend hours of service.

4.3.2 Impacts and Alternate Scenarios

4.3.2.1 Future Kerosene Demand

Like other household energy issues, residential lighting impacts can progress in a cascade, beginning with issues associated with access and demand itself (e.g. subsidies) and ending with downstream impacts resulting from its use. The Environmental Health Pathway, for example, has been used to describe the progression from raw fuel to disease outcomes in the context household cooking (*47*).

Figure 4.3.4 presents estimated demand for lighting kerosene to 2030 under selected alternate scenarios; corresponding values are presented in **Table 4.3.3**. Implications of efforts to attempt to supplant demand for kerosene with pico-solar LED lamps are discussed, but not shown in **Figure 4.3.4** since it assumes full trade-out.

A gradual reduction in demand is expected under the Baseline scenario but persists beyond 2030, indicating a continued reliance on non-grid lighting energy. Universal connection to electricity (UC) with no changes to service reliability provides a modest reduction of 10% between 2010-2030 relative to Baseline. Coupling access with improvements to supply reliability (UCS) yields a more substantial reduction of 30% over the same period, or an additional 20% reduction from the UC scenario. The benefits of electrification in the future are attenuated in part by adjustments for future income growth on kerosene lighting energy consumption (See **Section 6.4.2.4.3**).

The most drastic deviations from Baseline that do not assume replacement occur as a result of changes in kerosene pricing. Between 2005 and 2030, total demand is reduced by 80% from Baseline as a result of subsidy phase-out (SPO). This high price sensitivity also results in a near doubling of demand above Baseline by 2030 under the full subsidy scenario (FS) used for bounding. The magnitude of these changes is sensitive to assumptions of demand elasticity, but the overall trends are similar: lighting needs persist beyond 2030, electricity supply reliability improvements yield the greatest savings of electrification scenarios and the reduction of the subsidy yields the greatest reductions.

There is limited research into the willingness to pay or subsidy impacts for household energy provisions, especially in the context of fuel-based lighting. A pilot study conducted in rural India found drastic reductions in kerosene consumption after subsidies were removed in place of unconditional cash transfers equivalent to the subsidy amount

(*48*). Within four months of implementation, village level consumption had fallen roughly 85%, from 82,000 to 13,000 liters/month. Results are indicative of high price sensitivities, however, it was unclear how and if lighting needs were continuing to be met.

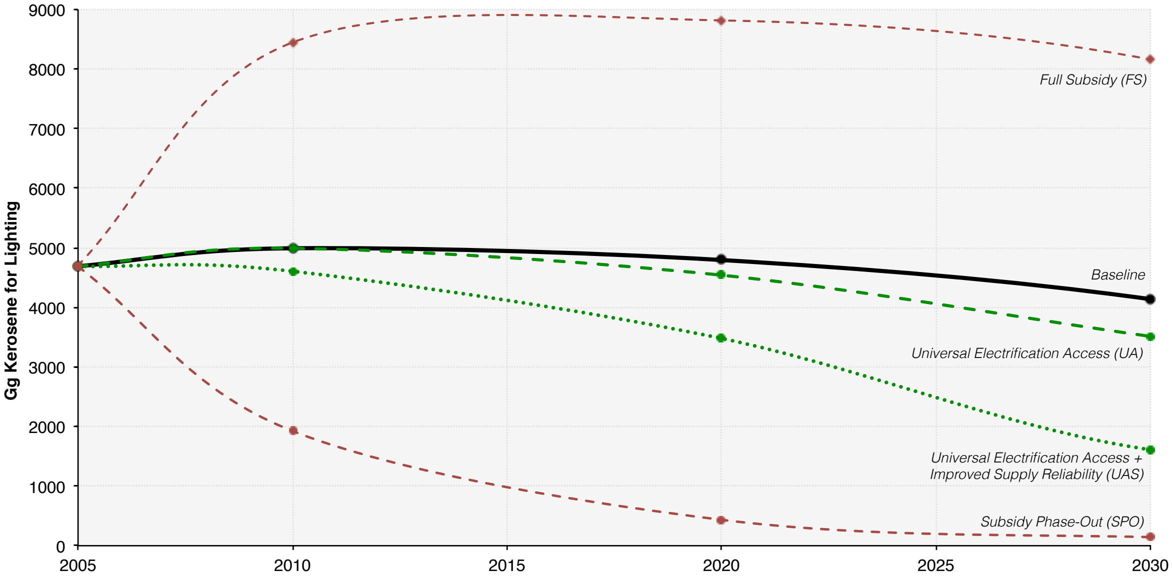


Figure 4.3.4 Estimated kerosene lighting demand (Gg) from the base year (2005) to 2030 under various alternate scenarios (top to bottom): Full Subsidy (FS), Baseline, Universal Electrification (UC), Universal Electrification and Improved Supply Reliability (UCS), Subsidy Phaseout (SPO).

Table 4.3.3. Demand for kerosene (Gg) for residential lighting in 2005-6 and estimated future demand under alternate scenarios in 2020 and 2030. Values in parentheses represent the percentage change from the Baseline scenario.

	2005	**2020**	**2030**
Baseline	4700 (-)	4800 (-)	4100 (-)
Universal Access 2030 (UC)	4700 (-)	4500 (-6%)	3500 (-15%)
UC+ Supply Reliability 2030 (UCS)	4700 (-)	3500 (-27%)	1600 (-61%)
Subsidy Phase-out (SPO)	4700 (-)	400 (-92%)	100 (-98%)
Full Subsidy (FS)	4700 (-)	8800 (83%)	8200 (100%)

4.3.2.2 Pollutant Emissions and Outdoor Primary $PM_{2.5}$ Impacts

The $PM_{2.5}$ emission rate for residential kerosene lighting in 2005, considering primary and backup use, was estimated at 250 Gg, increasing national emissions by 3-4% based on GAINS inventories. Unlike many anthropogenic aerosol sources, most of the particulate emissions are black carbon (230 Gg BC). The addition of lighting activities increases national BC emissions by as much as 20-25% based on GAINS inventories.

Organic carbon (OC) and sulfur dioxide are not major constituents in the emissions of kerosene light sources (*12*) and constituting approximately 0.5% of total national emissions for both pollutants. The majority of fuel carbon is emitted as carbon dioxide (CO_2). CO_2 emissions are estimated at 13,000 Gg (13 Mt), constituting less than one percent of national CO_2 emissions.

Approximately 60% of the $PM_{2.5}$ emissions from kerosene lighting in 2005 were attributed to use by electrified households (secondary users). Emissions do not scale proportionally with consumption due to differences in lighting device stock and associated emission factors over sub-populations, but trends are similar. The proportion of emissions attributed to secondary users was much higher than the national average in urban areas (85%) where electricity connection rates exceed 90%, and were more evenly distributed in rural areas (45% secondary). General trends in emissions under alternate scenarios track those of demand, ranging from reductions of 18% (*UC*) to 96% (*SPO*) when kerosene demand is effectively reduced by 2030, but do not assume full replacement (*Solar*) (**Figure 4.3.5**).

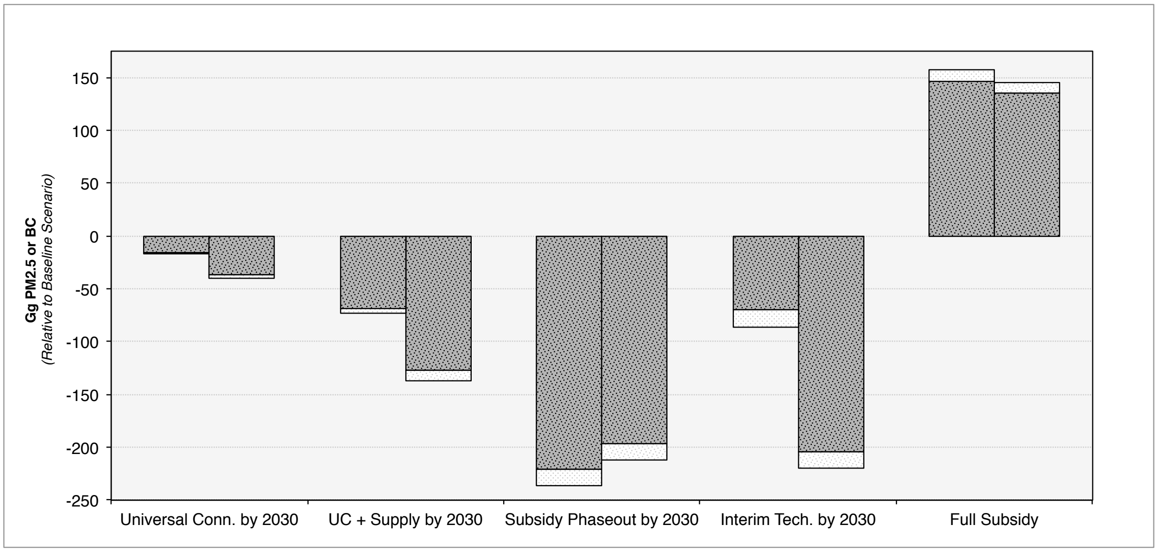


Figure 4.3.5. Estimated $PM_{2.5}$ emissions from residential kerosene lighting over selected alternate scenarios in 2020 (left column) and 2030 (right column). The darker layer of each bar corresponds to the proportion of $PM_{2.5}$ emissions that is black carbon (BC).

Updates to GAINS inventories to include residential lighting were used to estimate years of lost life due to from exposure to primary outdoor $PM_{2.5}$ among adults. $PM_{2.5}$ health impacts in GAINS were measured in years of lost life due to early mortality (YLL) and do not include life years lost due to disability (YLD). $PM_{2.5}$ impacts are aggregated over all anthropogenic activities; thus changes in YLL under alternate scenarios are evaluated relative to the Baseline scenario in 2020 and 2030 evaluation years. Impacts are not disaggregated into primary or secondary use for lighting due to the complexity and uncertainty in allocating these parameters within GAINS.

Outdoor primary $PM_{2.5}$ health impacts from kerosene lighting in the base year were modest by comparison to other anthropogenic pollutant sources; nevertheless, alternate scenarios that reduce the use of kerosene do result in YLL reductions (**Figure 4.3.6**). Efforts to improve electricity connection and supply by 2030 provide a 0.5-2% reduction in primary $PM_{2.5}$ YLLs (270-970 thousand YLL) relative to Baseline, while mitigating its use as a result of pricing (*SPO*) or substitution (*Solar*) resulted in more substantial 3-4% (1.4-1.7 million YLL) reductions.

Efforts to offset kerosene lighting with technologies independent of the grid by 2030 (*Solar*) resulted in the largest benefits (1.7 million YLL), since full replacement is assumed regardless of primary or secondary use status. In 2030, averted YLLs under the *Solar* scenario are 1.8 times that of the highest electricity service scenario (UCS) and 15% greater than removal of the subsidy.

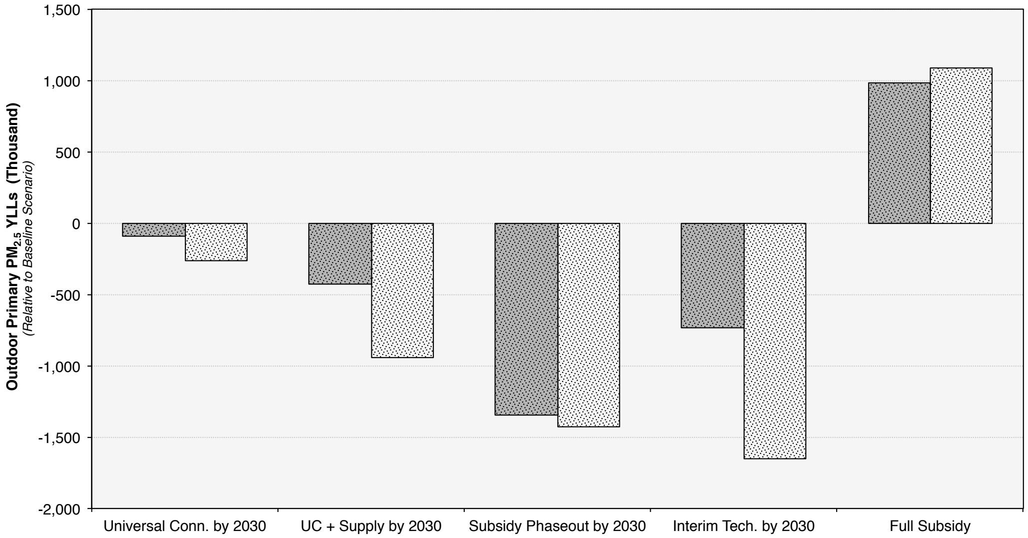


Figure 4.3.6. Change in years of life lost (YLL) due to primary $PM_{2.5}$ relative to the Baseline Scenario for alternate scenarios in 2020 (dark) and 2030 (light).

4.3.2.2.1 $PM_{2.5}$ Control Costs: Pico-Solar LED

Information on kerosene lighting characteristics used to estimate control costs for primary $PM_{2.5}$ from kerosene lighting using household pico-solar lighting. Previously, I have assumed the *Solar* scenario as being representative of any technology not reliant on the growth of the central electrification grid. For exploratory control cost estimates, I assume the replacement technology to be pico-solar LED lanterns, equivalent to those currently being promoted as part of the Lighting Global initiative (http://www.lightingglobal.org), among other efforts. These devices are approved using quality assurance testing protocols developing by Lighting Global, and can be purchased locally for $25-50. Typical solar lamps include multi-year warranties on the battery and PV cell and additional charging functionality for phones on lamps at the upper end of the price scale. Baseline kerosene technology is assumed to be kerosene-fueled simple wick lamps and hurricane lanterns. More detailed description of control cost estimates are provided in **Section 6.4.3.4.1**.

Control costs for pico-solar lighting relative to basic kerosene technology are negative (cost savings), varying from 3 - 10 \$/kg $PM_{2.5}$, under conservative assumptions. As an exploratory estimate, the control of implementing kerosene hurricane lanterns, which is kerosene-fueled but less polluting, is approximately 0.5-1.5 \$/kg $PM_{2.5}$. As a result of the reduced reliance on kerosene, the total $PM_{2.5}$ control cost of kerosene lighting in 2030 is negative, indicating a savings of approximately 3.5 billion USD.

4.3.2.3 Economic Impacts

Deadweight loss (DWL) from the subsidization of kerosene for lighting in 2005 was estimated at 950 million USD. By comparison, the under recovery by oil companies in the same year has been estimated at 3.3 billion USD (*27*). Conservative estimates assuming unit elasticity and linear demand yield a lower bound estimate of 200 million USD.

Approximately 20% of the DWL from the subsidization of kerosene for lighting was a result of consumption by non-electrified households, indicating that the majority of economic inefficiency was due to use as a secondary source of lighting. This implies that the majority of DWL is a result of issues such as unreliable electricity supply and latent demand due to tasks where electricity cannot be used. **Figure 4.3.7** illustrates DWL across urban and rural expenditure groups and disaggregated by electricity service level; corresponding values are presented in **Table 4.3.4**. For kerosene lighting, the social cost of carbon acting through climate change is estimated at \$70 million for CO_2 and \$850 million for BC using CO_2 equivalence. This is roughly equivalent to DWL even before considering other externalities of residential kerosene consumption. More detailed description of social cost estimates is available in **Section 6.4.3.4.2.**

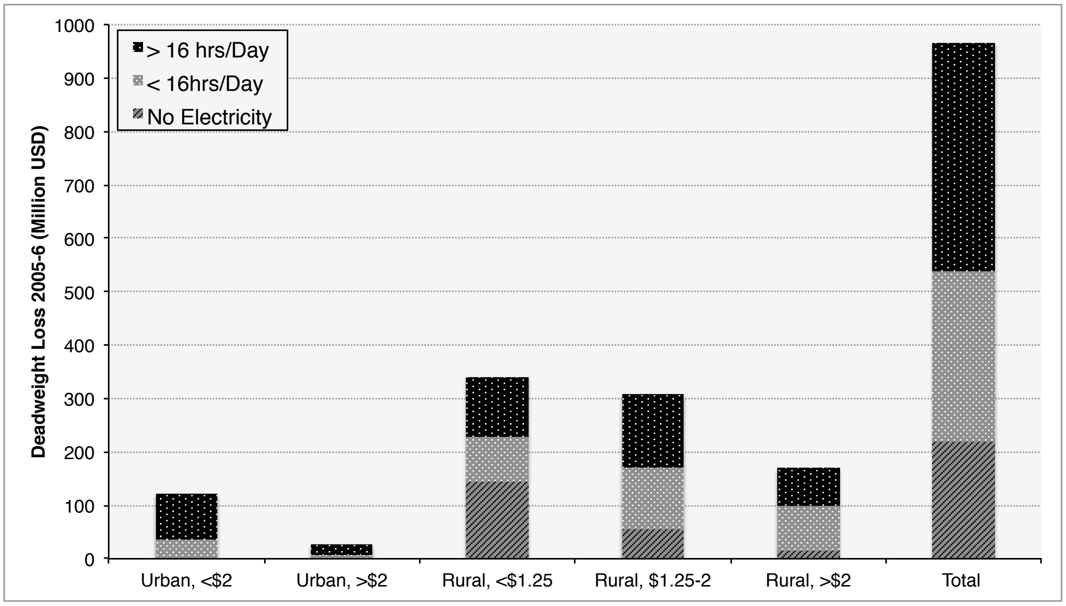


Figure 4.3.7. Deadweight loss estimates of kerosene used for lighting for 2005 by expenditure and electricity sub-populations.

Table 4.3.4. Estimated deadweight loss (million USD) from subsidization of kerosene for lighting in 2005 across expenditure and electricity supply groups.

	No Electricity	**< 16 hrs/day Electricity Supply**	**> 16 hrs/day Electricity Supply**	**Total**
Urban, <$2	(--)	36.4	85.5	**122**
Urban, >$2	(--)	7.3	19.8	**27.1**
Rural, <$1.25	145	83	113	**341**
Rural, $1.25-2	56.3	113	138	**308**
Rural, >$2	16.6	81	72.0	**169**
Total	218	321	428	**967**

4.4 SUMMARY AND CONCLUSIONS

This study is among the first detailed assessments of the use of kerosene for residential lighting. An analysis of a national expenditure survey was performed to evaluate differences and trends in the use of kerosene for residential lighting across heterogeneous population groups. Consumption characteristics were used to inform the development of a service demand model and test the effect of improvements to electricity access, electricity reliability, fuel price on future kerosene demand and associated health impacts acting through air pollution. I also explore how access to grid-independent clean lighting technology could alter kerosene lighting impacts in the future. The economic inefficiency resulting from the subsidization of kerosene for lighting was quantified, and compared to the social cost of pollutant emission externalities acting through climate. Finally, to the extent possible, I explore secondary use of kerosene for lighting. The analyses presented here can undoubtedly be refined, but are a step towards better understanding the role of lighting in the household energy system. Results also begin to summarize the potential importance of household lighting in the context of health, environment and economic welfare; topics more extensively covered for other activities in the household energy system.

Fuel-based lighting in the residential sector is not specific to India, but India does contain a large proportion if the global user population (see **Chapter 2** and citations within). Furthermore, the availability of nationally representative datasets containing detailed household energy characteristics allowed for more depth and flexibility in analysis than would have been possible elsewhere. It is the hope that analyses and results presented here provide a guide by which to inform and expand to analyses in other countries with residential lighting needs, although the level to which lessons learned in the Indian context accurately reflect their situations remains to be seen.

Household surveys indicate that lighting is often the first application of electricity upon achieving connection (*7*). However, connection does not imply access and electrified homes may continue to rely on fuel-based light sources for supplementary illumination or during supply interruptions (load-shedding) (*29*). In India, kerosene used for lighting in houses with electricity connections constituted an approximately equal share of demand as non-electrified (primary) households in 2005. Clear differences are observed across groups differing in electricity reliability level, illustrating the general importance of considering electricity reliability in evaluations of lighting and electrification. In rural areas, in particular, kerosene demand for lighting persists even when electricity reliability improves. This suggests that, in addition to reliability, affordability and unmet demand may still be important to some rural consumers and adds further impetus to consider strategies that address lighting needs among electrified households. In aggregate, groups with unreliable electricity may contribute the majority of total burden associated with fuel-based lighting in India.

Results from alternate scenarios suggest that little change in kerosene demand, or reliance on other fuel-based lighting sources in general (e.g. candles, other oil foils, LPG), can be expected till 2030 (less than 10% as compared to Baseline) if electricity coverage improves, but no further improvements occur in the quality and reliability of supply. We find kerosene lighting demand to be highly price sensitive, so that in a scenario in which current subsidies are phased out, kerosene demand drops by 97% compared to the Baseline by 2030. It is unclear, however, if and how lighting services would be met under conditions where other lighting alternatives are not made accessible. From existing cases in Nepal and parts of Sub-Saharan Africa, there is evidence that in the absence of kerosene, homes often substitute with paraffin candles that provide equally poor service and are also polluting.

4.4.1 Considering Secondary Sources of Energy

Energy and technology "stacking" of residential lighting sources is known to occur based on field observations and from a limited body of peer-reviewed literature. The associated demand and impacts of secondary use of kerosene for lighting, however, has been less understood. When secondary demand is accounted for, it is often reliant on approximations as opposed to inferences from more robust population-based surveys. These shortcomings stem in large part from limitations of current household surveys.

The importance of considering impacts from secondary-user populations for lighting highlights a general need to develop household energy evaluations that better reflect the complexity of multiple energy use in low and middle-income countries. Energy stacking was first recognized in the context of residential cooking and is now well accepted in the household energy literature (*49*). The benefits and methods of mitigating reliance on polluting fuels used as secondary energy sources, however, is just beginning to be understood.

Efforts to mitigate secondary use of polluting fuels and technologies will likely play a growing role in future household interventions and merit more consideration in household energy impact assessments and projections. National expenditure surveys, for example, are important resources for developing pollutant inventories and metrics used to inform on the health, environment and economic consequences of household energy. Unfortunately, many of the large-scale survey instruments used heavily to assess progress and inform program design have not evolved in kind, often providing little more than characteristics of "primary" energy sources.

An incremental step in improving our understanding is to simply re-examine the way in which current questions are framed. As opposed to classifying "primary" fuels for specific activities, surveys should instead emphasize the use of fuels first, supplementing with information on quantities and end-use activities by fuel. This allows for more flexibility in responses by the households and less rigidity in classification during analysis. Also, with growing access to electricity connections, the role of reliability becomes increasingly important to quantify, as obtaining information from utility companies in low and middle-income countries can be notoriously difficult. In the absence of objective measures, surveys could ask respondents for number of hours per day they experience load shedding at various times of the year. In smaller-scale studies, objective measures of appliance usage and grid reliability could be used to validate self-reported information.

4.4.2 Solutions in the Absence of the Grid

The impacts of residential kerosene lighting in India may be significant, providing an opportunity to improve population welfare while alleviating economic burdens associated with kerosene subsidies. Reduction in $PM_{2.5}$ from kerosene sources are estimated to avert 270 thousand to 1.7 million years of life lost from primary outdoor $PM_{2.5}$ exposures among adults in 2030.

Initial estimates of $PM_{2.5}$ control costs for offsetting kerosene lighting with currently available pico-solar lighting devices indicates a net savings of approximately $4 billion by 2030 as a result of reduced reliance on kerosene. Shifting financial support away from kerosene, which is both polluting and prone to leakage, towards these cleaner lighting options would appear to be a “no regrets” option based on preliminary analysis. It is perhaps important to note that some of the issues associated with residential lighting but relevant to development are not addressed here. To name a few that are commonly discussed in the literature but not always formally measured are acute health impacts such as kerosene-related skin burns, poisonings and indoor air quality impacts. Educational performance and income generating activities are also frequently referenced motivations for lighting and electrification programs.

Study results also highlight a need for investigations that measure the effects of mitigating kerosene use at the household level, and also evaluate the performance of programs that aim to improve lighting services. Furthermore, although the cost effectiveness of currently available lighting technologies is promising, their viability is still contingent upon access to replacement technology, where access can imply their availability in markets as well as financial access. Annualized costs mask important distinctions between the cost structure of kerosene and pico-solar technology that may have implications on household access. The majority of kerosene costs are associated with incremental fuel costs, while pico-solar devices are almost entirely upfront investment costs combined with good after sales service/warranties. Innovative financing schemes that convert lump sum upfront costs into a stream of smaller and more regular payments that align better with household cash inflows can be an important means for improving the affordability of such devices. There also exists the potential option to shift a portion of funds currently used to subsidize kerosene towards cleaner lighting options, albeit only with high-level policy interventions.

It is important to note that there are a variety of alternatives for providing cleaner lighting solutions to households in the absence of central grid electricity. De-centralized electrification, for example, would provide a variety of additional benefits beyond lighting. For households with unreliable electricity, inverters and LED socket bulbs that charge when electricity is available are potential options. The choice in using pico-LED was based on its ability replace lighting needs in kerosene using households regardless of electricity status and to do so with minimal infrastructure at the distributional or household levels.

4.4.3 Welfare Impacts of Subsidizing Kerosene for Lighting

Deadweight loss from subsidization of kerosene for lighting is estimated to be substantial. In 2005, the cost of additional kerosene consumed for lighting purposes as a result of the subsidy was valued at between $200 to $950 million. Roughly three quarters of this DWL was attributed to use by households for secondary lighting. For comparison, under-recovery in 2005 for all kerosene subsidies in India was valued at $3.3 billion (*27*).

Fossil fuel subsidies are unique because of their potential for incurring social impacts. Social costs of global subsidies on gasoline and diesel, for example, have been valued at approximately $33 billion in 2012, equal to approximately three quarters of associated deadweight loss (*50*). Kerosene's use as a lighting fuel in India is likely not an exception. The social costs of carbon dioxide and black carbon emissions alone are estimated to be comparable to deadweight loss. This is before considering other externalities such as the value of direct health impacts resulting from outdoor air pollution. These external social costs are an addition to DWL and therefore not included in fuel or subsidy costs at any level.

It is important to note, however, that the net social cost value of fossil fuel subsidies is not necessarily always positive (worse off) across all contexts. When considering subsides for household energy, for example, it is important to consider the effect on offsetting use of competing fuels that may also carry social costs. For example, the efficiency and health gains from shifting kerosene subsidies to more energy dense LPG in Indonesia, based on current indications, has led to a reduction in economic inefficiency (*28*) and may have had social benefits as a result of cleaner combustion, although there still exists a need for more in-depth assessment. Kerosene lighting is already quite low on the spectrum of lighting options. Thus, in the absence of a subsidy it may become more important to consider access to alternative sources of illumination independent of the grid.

The subsidization of kerosene in India is a case where few technical arguments can be made in its favor. Kerosene is a highly flexible and robust fuel allowing for wide variety applications, making it vulnerable to leakage (*14, 51*). The similarity to diesel means that diversions to the automobile transport sector are likely if fuel prices and associated subsidies are not considered together. In recent years, access to more efficient energy sources (e.g. LPG) and technologies (e.g. pico-solar) has made kerosene obsolete in both service and efficiency. Even subsidization of most of these alternatives would likely impose a lower economic burden and social cost than exists with kerosene. The subsidies persist, however, because of strong political pressures.

4.5 REFERNCES

1. K. R. Smith, A. Woodward, D. Campbell-Lendrum, D. Chadee, Y. Honda, Q. Liu, J. Olwoch, B. Revich, R. Sauerborn, "WGII AR5 Human health: Impacts, adaptation, and co-benefits," (IPCC, 2014).
2. S. S. Lim, T. Vos, A. D. Flaxman, G. Danaei, K. Shibuya, H. Adair-Rohani, M. Amann, H. R. Anderson, K. G. Andrews, M. Aryee *et al.*, A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **380**, 2224-2260 (2012).
3. D. Shindell, J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes *et al.*, Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335**, 183-189 (2012).
4. N. Unger, T. C. Bond, J. S. Wang, D. M. Koch, S. Menon, D. Shindell, S. Bauer, Attribution of climate forcing to economic sectors. *Proc. Nat. Acad. Sci. USA* **107**, 3382-3387 (2010).
5. T. C. Bond, E. Bhardwaj, R. Dong, R. Jogani, S. Jung, C. Roden, D. G. Streets, S. Fernandes, N. Trautmann, Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochemical Cycles* **21**, (2007).
6. Sustainable Energy For All, "Global Tracking Framework," (2013).
7. The World Bank, "The welfare impact of rural electrification: A reassessment of the costs and benefits," (The World Bank Independent Evaluation Group, Washington DC, 2008).
8. T. Bernard, M. Torero, "Bandwagon effects in poor communities: Experimental evidence from a rural electrification program in Ethiopia " (International Food Policy Research Institute, Washington DC, 2013).
9. B. Tanguy, Impact analysis of rural electrification projects in sub-Saharan Africa. *The World Bank Research Observer* **27**, 33-51 (2012).
10. M. Barron, University of California, Berkeley, Berkeley, CA (2013).
11. E. Mills, The specter of fuel-based lighting. *Science* **308**, 1263-1264 (2005); published online EpubMay 27, 2005.
12. N. L. Lam, Y. Chen, C. Weyant, C. Venkataraman, P. Sadavarte, M. A. Johnson, K. R. Smith, B. T. Brem, J. Arineitwe, J. E. Ellis *et al.*, Household Light Makes Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps. *Environmental Science & Technology* **46**, 13531-13538 (2012).
13. P. Alstone, P. Lai, E. Mills, A. Jacobson, High life cycle efficiency explains energy payback for improved off-grid lighting systems. *Journal of Industrial Ecology* **In Press**, (2014).
14. N. L. Lam, K. R. Smith, A. Gauthier, M. N. Bates, Kerosene: a review of household uses and their hazards in low- and middle-income countries. *Journal of Toxicology and Environmental Health, Parth B: Critical Reviews* **15**, 396-432 (2012).

15. D. Kimemia, C. Vermaak, S. Pachauri, B. Rhodes, Burns, scalds and poisonings from household energy use in South Africa: Are the energy poor at greater risk? *Energy for Sustainable Development* **18**, 1-8 (2014).
16. E. Mills, "Health impacts of fuel based lighting," *Lumina Project Technical Report #10* (2012).
17. M. D. Peck, G. E. Kruger, A. van der Merve, W. Godakumbura, R. B. Ahuja, Burns and fires from non-electric domestic appliances in low and middle income countries. Part 1. The scope of the problem. *Burns* **34**, 303-311 (2008).
18. A. K. Pokhrel, M. N. Bates, S. C. Verma, H. S. Joshi, C. T. Sreeramareddy, K. R. Smith, Tuberculosis and Indoor Biomass and Kerosene Use in Nepal: A Case-Control Study. *Environ Health Perspect* **118**, (2010).
19. M. N. Bates, R. K. Chandyo, P. Valentiner-Branth, A. K. Pokhrel, M. Mathisen, S. Basnet, B. R. Shrestha, T. A. Strand, K. R. Smith, Acute lower respiratory infection in childhood and household fuel use in Bhaktapur, Nepal. *Environ Health Perspect* **121**, 637-642 (2013).
20. M. B. Epstein, M. N. Bates, N. K. Arora, K. Balakrishnan, D. W. Jack, K. R. Smith, Household fuels, low birth weight and neonatal death in India: the separate impacts of biomass, kerosene, and coal. *International Journal of Hygiene and Environmental Health* **216**, 523-532 (2013).
21. J. Apple, R. Vicente, A. Yarberry, N. Lohse, E. Mills, A. Jacobson, D. Poppendieck, Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air* **20**, 399-411 (2010).
22. E. D. S. Van Vliet, K. Asante, D. W. Jack, P. L. Kinney, R. M. Whyatt, S. N. Chillrud, L. Abokyi, C. Zandoh, S. Owusu-Agyei, Personal exposures to fine particulate matter and black carbon in households cooking with biomass fuels in rural Ghana. *Environmental research*, 1-9 (2013).
23. T. Bond, Bounding the role of black carbon in the climate system: a scientific assessmnet. *American Geophysical Union*, (2013).
24. G. Habib, C. Venkataraman, T. C. Bond, J. J. Schauer, Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels. *Environ Sci Technol* **42**, 8829-8834 (2008).
25. A. Jacobson, N. L. Lam, T. C. Bond, N. Hultman, "Black carbon and kerosene lighting: an opportunity for rapid action on climate change and clean energy for development," *Global Views: Global Economy and Development* (The Brookings Institution Washington DC, 2013).
26. D. N. Rao, Kerosene subsidies in India: When energy policy fails as social policy. *Energy for Sustatinable Development* **16**, 35-43 (2012).
27. B. V. Shenoy, "Lessons learned from attempts to reform India's kerosene subsidy," (International Institute for Sustainable Development (IIST), Geneva, Switzerland, 2010).
28. H. Budya, M. Y. Arofat, Providing cleaner energy access in Indonesia through the megaproject of kerosene conversion to LPG. *Energy Policy* **39**, 7575-7586 (2011).
29. I. H. Rehman, P. Malhotra, R. C. Pal, P. B. Singh, Availability of kerosene to rural households: a case study from India. *Energy Policy* **33**, 2165-2174 (2005).

30. Energy Resources Institute, International Institute for Sustainable Development, "Evaluation of the pilot project on direct transfer of kerosene subsidies in Kotkasim, Alwwar," *GSI Report* (The International Institute of Sustainable Development, Geneva, Switzerland, 2014).
31. K. S. Parikh, "Report of The expert group on a viable and sustainable system of pricing petroleum products," (New Delhi, India, 2010).
32. K. S. Parikh, P. K. Singh, S. Garg, "Report of the expert group to advise on the pricing methodology of diesel, domestic LPG and PDS kerosene," (New Delhi, India, 2013).
33. S. Desai, R. V, NCAER. (Inter-university Consortium for Political and Social Research Ann Arbor, 2009).
34. O. R. Messner, M. Strubegger, "User's guide for message iii," (International Institute of Applied Systems Analysis, 1995).
35. M. Amann, I. Bertok, J. Borken, A. Chambers, J. Cofala, F. Dentener, C. Heyes, J. Kejun, Z. Klimont, M. Makowski *et al.* (International Institute of Applied Systems Analysis (IIASA), Laxenburg 2008).
36. S. Pachauri, J. B. Ruijven, Y. Nagai, K. Riahi, D. Vuuren, A. Brew-Hammond, N. Nakicenovic, Pathways to achiev universal household access to modern energy by 2030. *Environmental Research Letters* **8**, (2013).
37. K. Riahi, F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, D. McCollum, S. Pachauri, S. Rao *et al.*, in *Global Energy Assessment - Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012), pp. 1203-1306.
38. Lighting Global, in *IEC/TS 62257-9-5*. (International Electrotechnical Commission, 2014).
39. P. Purohit, M. Amann, R. Mathur, P. Bhandari, I. Bertok, J. Borken, J. Cofala, C. Heyes, Z. Klimont, P. Rafaj *et al.*, "GAINS-Asia: Scenariso for cost effective control of air pollution and greenhouse gases in India," (International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria, 2010).
40. M. Krol, S. Houweling, B. Bregman, M. van den Broek, A. Segers, P. van Velthoven, W. Peters, F. Dentener, P. Bergamaschi, The two-way nested global chemistry-transport zoom model TM5: algorithm and applications. *Atmos. Chem. Phys.* **5**, 417-432 (2005).
41. R. Mechler, M. Amann, W. Schopp, "A methodology to estimate changes in statistical life expectancy due to the control of particulate matter air pollution," *Iterim Report* (International Institute of Applied Systems Analysis, Laxenburg, Austria, 2002).
42. C. A. Pope, R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, G. Thurston, Lung cancer, cardiopulminary mortality and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association* **287**, 1132-1141 (2002).
43. C. A. Pope, M. Ezzati, D. W. Dockery, Fine particulate air pollution and life expectancy in the United States *The New England Journal of Medicine* **360**, 376-386 (2009).

44. M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj *et al.*, Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software* **26**, 1489-1501 (2011); published online Epub12//.
45. NSSO, "Household consumption of various goods and services in India, NSS 61st Round (July 2004 - June 2005), Report No. 509 (61/1.0/2)," (National Sample Survey Organisation, New Dehli, 2007).
46. NSSO, "Energy sources of India household for cooking and lighting, NSS 61st Round (July 2004 - June 2005), Report No. 511 (61/1.0/4)," (National Sample Survey Organisation New Dehli, 2007).
47. K. R. Smith, *Biomass fuels, air pollution, and health: A global review*. (Plenum Books, New York, 1987).
48. TERI, "Fossil-fuel subsidy reform in India: Cash transfers for PDS kerosene and domestic LPG," (The International Institution of Sustainable Development, Geneva, 2012).
49. O. R. Masera, B. D. Saatkamp, D. M. Kammen, From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development* **28**, 2083-2103 (2000).
50. L. W. Davis, in *Working Paper,* B. University of California, Ed. (Berkeley, CA, 2014).
51. G. Ritchie, K. Still, J. Rossi, M. Bekkedal, A. Bobb, D. Arfsten, Biological And health effects of exposure to kerosene-based jet fuels and performance additives. *Journal of Toxicology and Environmental Health. Part B, Critical Reviews* **6**, 357 - 451 (2003).

5.0 Chapter 5

Summary and Conclusions

5.1 Summary & Conclusions

The use of dirty fuels and inefficient technologies to meet residential energy needs in low- and middle-income countries can result in adverse impacts to health, the environment and the economy. Most of the current evidence on household energy impacts and potential benefits of cleaner fuels and technologies focuses on residential cooking with solid fuels, specifically biomass and coal. There is little question that increasing access to cleaner cooking technologies is of major importance, but there often exist other household energy issues in the home that have received less attention in the literature. This work focused on increasing the understanding of two household energy topics that have received less attention to-date: the use of kerosene fuel for cooking and residential lighting.

On the face of it, some of the topics and themes in this dissertation may seem a stretch from what is traditionally examined in environmental health research. The original impetus of this effort was to better characterize the pollutant impacts from residential lighting, an issue I saw as being under-represented in the household energy literature. Over time, however, I felt the research boundaries required expansion in order to provide a more thorough consideration of what I saw as important factors underlying the use of kerosene and access to alternatives. For example, fuel subsidies and electricity service level may seem at first glance to have little direct impact on the environment or human health. I believe this research illustrates, however, that these distally related issues are important for influencing energy choices and, therefore, their associated impacts. As a result, these distal factors can play an important role in intervention strategies aimed at preventing future impacts.

5.1.1 Pollutant Emissions

Chapter 2 focused on establishing pollutant emission characteristics of kerosene lighting devices and quantifying their global contributions. While the final impacts of emissions are not reported in the chapter, results provided the foundation for impact estimates in **Chapter 4** and in an evaluation of climate impacts not presented here (*1*). Particulate matter (PM) emission factors for kerosene lamps were consistent with several previous, but less detailed, studies on kerosene lighting sources (*2-4*). Despite relatively low rates of fuel consumption, kerosene lamps were found to convert as much as 7-9% of kerosene to PM, resulting in emission factors that were several times to an order of magnitude greater than for kerosene cooking stoves.

The large elemental carbon fractions of emitted particulate carbon were unique among household combustion sources, providing a new and potentially important dimension to kerosene lighting emissions. While many anthropogenic sources of particulate aerosol are mixtures of organic (OC) and elemental carbon (EC, used here interchangeably with BC), nearly all aerosol carbon from kerosene lamps was BC (>95% by mass). Few known anthropogenic sources emit such high fractions of particulate aerosol in the BC component and so little of species with opposing cooling effects. Global emission rate estimates suggest that lighting is not a leading contributor of BC, even at the residential level, but its mitigation could play an immediate, albeit modest, role in reducing contribution to an important short-term climate warmer, while potentially delivering household welfare co-benefits.

This study is among the first to quantify the global impact of pollutants from residential lighting and establishes the groundwork for future efforts to refine and improve these estimates. Household lighting characteristics were estimated from the best available information – including national surveys, market surveys, grey literature and peer-reviewed literature – however, a small degree of additional information could improve estimates considerably. Uncertainty analyses indicated that a large fraction of the uncertainty in total emissions could be attributed to bottom-up factors influencing fuel consumption – specifically, hours of use and burn rate of the fuel. Direct use of household consumption data could sidestep some of the uncertainty in these bottom-up approaches, but would require information to apportion between lighting and other kerosene end-use activities. This could also provide insights into the degree of secondary lighting demand, which was accounted for in India but not for other countries or regions. **Chapter 4** attempts to fill some of these gaps in an analysis of India by using self-reported consumption data and end-use activity of fuels.

5.1.2 Concentration: Markers for Complex Pollutant Mixtures

The link between kerosene source emissions and household health impacts requires a measure of exposure. Recent epidemiological evidence based on self-reported use of kerosene as a cooking or lighting fuel is suggestive of potential adverse health risks. The magnitude of health risk estimates, however, is not entirely consistent with what would be expected from estimated pollutant concentrations or inferred from emission rates of particulate matter – the most common marker used in household air pollution studies.

Informed by results from **Chapter 2**, **Chapter 3** explores whether the addition of polycyclic aromatic hydrocarbons (PAH), elemental carbon (EC) and organic carbon (OC) could provide additional information beyond what is inferred from typical markers of pollution in household air pollution and exposure studies – undifferentiated PM mass and carbon monoxide (CO). Area concentrations were measured during the operation of combustion sources used for cooking and lighting in the Kaski District of Nepal: a chulo wood stove (traditional), kerosene stove, sawdust stove, kerosene wick lamp and paraffin candle. Standard pollutant markers – undifferentiated PM mass and carbon monoxide– were measured along with potential supplement markers - sixteen PAH and particulate EC and OC. In some instances, multiple methods of measuring a pollutant were used and compared.

PAH concentration trends, as well as EC and OC concentrations, were not always reflective of PM or CO, suggesting that their use to supplement standard markers of pollution could provide added information. Results from the sawdust stove were especially illustrative of this benefit. $PM_{2.5}$ concentrations during use of the sawdust stove were roughly three times less than produced by the chulo, but concentrations of fourteen EPA priority PAH (PAH_{14}) were three times greater than produced by the chulo.

Furthermore, depending on the marker being applied, fold differences in pollutant concentrations across appliances ranged from as little as a factor of four (naphthalene) to over a hundred (PAH_{14}).

Results also contradicted the use of retene as a source marker for softwood combustion. Retene was detected during use of the kerosene stove at levels on average ten times greater than during use of the chulo wood stove. A recent emissions study on coal cookstoves also detected high retene levels, indicating need for caution over the use of retene as a source-specific marker (*5*). Source identification has not been a major priority of household air pollution studies, but may become important for understanding impacts on outdoor air quality, differentiating exposures in households using multiple combustion sources and differences in pollutant mixture toxicities.

Chapter 3 relies upon a series of controlled experiments to provide the most information from the least number of samples. These results do not represent exposure and measurements were not subject to the effect of behavioral determenents, which could modify conclusions about the comparative risks associated with the different sources. Future efforts will be needed to determine effective methods to sample for longer durations under actual household conditions, and adapting PAH and EC collection procedures for personal monitoring. Finally, this work is only a partial analysis of all the samples collected during the sampling campaign and requires completion.

5.1.3 Drivers, Sources & Impacts

Household energy impacts are predicated on the consumption, of access to, and dependence on dirty fuels or inefficient technology. For many households, access to kerosene is often only enabled through government subsidies and used as a lighting fuel only in the absence of electricity or cleaner alternatives. **Chapter 4** was an in-depth analysis of kerosene as a lighting fuel in India. I used an analysis of a nationally representative household survey to identify associations between the consumption of kerosene with fuel prices and electricity service levels. Flexibility in survey design allowed for apportionment between both primary and secondary consumption of kerosene for lighting. Survey-based relationships informed the design of a service-demand model, which was used to evaluate how changes to the fuel subsidy and electricity service levels would impact future kerosene demand, specifically for lighting. Consumption estimates were linked to the integrated assessment model GAINS (Laxenburg, Austria) to evaluate impacts on air quality. Estimated demand curves were used to calculate deadweight loss resulting from the kerosene subsidy and also apportion the economic burden to primary and secondary user populations. **Chapter 4** fills some gaps identified in **Chapter 2** by relying on self-reported activities as opposed to pure bottom-up analysis, and used self-reported activity data to account for secondary use of kerosene as a lighting fuel.

Results provide the most in-depth assessment of residential lighting with kerosene to-date, demonstrating the potential benefits of mitigation, but also linking potential impacts to upstream drivers related to energy policies. Households with unreliable electricity were found to consume over 60% of kerosene used for lighting activities during the survey period. This result highlighted the importance of considering electricity access as well as reliability level, and more generally the potential impact of energy stacking for lighting activities. Results from alternate scenarios where electricity access was improved suggested that little change in kerosene demand, or alternatively reliance on other fuel-based lighting sources (e.g. candles, other oil fuels, LPG), would be expected till 2030 if electricity coverage improves, but quality and reliability of supply does not.

Efforts to eleminate kerosene lighting in Indian households may improve population welfare while alleviating economic burdens associated with kerosene subsidies. Reductions in reliance on kerosene for light is estimated to avert 270 thousand to 1.7 million years of life lost from primary outdoor $PM_{2.5}$ exposures. The largest reductions result from actions that address populations relying on kerosene as a secondary lighting source. Initial estimates of $PM_{2.5}$ control costs for offsetting kerosene lighting with currently available pico-solar lighting devices suggest a net savings of approximately $4 billion in 2030, driven principally by reduced reliance on kerosene.

Kerosene lighting demand was found to be highly price sensitive, so that in a scenario in which current subsidies are phased out, kerosene demand drops by 97% by 2030 compared to the Baseline. It is unclear, however, if and how lighting services would be met under conditions where other lighting alternatives are not made accessible. From existing cases in Nepal and parts of Sub-Saharan Africa, there is evidence that in the absence of kerosene, homes often substitute with paraffin candles that provide equally poor service and are also polluting.

As a result of high price sensitivity, deadweight loss from subsidization of kerosene for lighting is estimated to be substantial. In 2005, the cost of additional kerosene consumed for lighting purposes as a result of the subsidy was valued at $200 to $950 million. Roughly three quarters of this DWL was attributed to use by households for secondary lighting. The subsidization of kerosene in India is a case where few technical arguments can be made in its favor. Results on economic impact further emphasize the need to consider the secondary user population and electricity reliability in household energy interventions.

The analysis also highlights several ways in which household surveys might be improved to allow for a wider range analysis. First, questions on lighting should be considered in household surveys. As a first step, these questions could be as simple as inquiring about primary fuel source, secondary fuel source and type of lighting device (e.g. simple wick, hurricane, LED lamp etc.). Another incremental step to improve surveys would be to re-design the way current questions are framed. Rather than classifying “primary” fuels for specific activities, surveys should instead inquire about the use of fuels first, supplementing with information on quantities and end-use activities by fuel. This sould allow for more flexibility in responses by the households and less rigidity in classification during analysis. Access to electricity is often asked, but rarely are measures of reliability. In the absence of objective measures, surveys could ask respondents for the typical number of hours per day they experience breaks in the electricity supply at various times of the year. In smaller-scale studies, objective measures of appliance usage and grid reliability could be used to validate self-reported information.

I have little doubt that the work and estimates provided in **Chapter 4** could be improved upon. The analyses and estimates presented benefitted from many sources of information, but in some cases required the use of informed assumptions to fill gaps in the data. This work is meant to be a first step, founded on the best available knowledge and data, and provide a groundwork from which future analyses can build, as more robust and rich data sets become available.

The IHDS dataset used to evaluate trends in consumption and to develop the demand model is a rich dataset, but has several limitations. As a survey collected in 2005, the information is outdated, especially in the context of a country as rapidly developing as India. Unfortunately, IHDS and NSSO surveys, collected in 2005 and released around 2007, reflect the most recent nationally representative consumption data available. IHDS is also cross-sectional in design, which means trends underlying future estimates are based on differences across population groups during the survey period (e.g. for expenditure, electricity supply). Panel (longitudinal) data would have provided a more ideal database for evaluating many of the effects explored in this study, but no such dataset existed (to my knowledge) with the necessary information on household energy.

5.2 Future Directions

The body of work presented here could be expanded and improved further. Available information on residential lighting, a major theme in this dissertation, is increasing but still limited. Basic information on residential lighting habits and trends will undoubtedly help to inform and improve future iterations of this research, specifically work presented in **Chapters 2** and **4**.

Research presented in **Chapter 3** is ongoing and an immediate task is to expand on current results to analyze all samples collected during the measurement campaign. Arguably, an effective marker is one that provides a robust and accurate measure of health risk, and future research will be needed to test whether PAH and EC measures contribute additional information to actual risk estimates. Wider use of supplemental markers will require improvements to sampling technology, analytical techniques and field-sampling methodologies to make them less invasive and more affordable for wide-scale use. Finally, based on results from **Chapter 2**, PAH and EC seem logical choices for markers but other supplemental markers likely exist.

Specific to **Chapter 4**, there are several research topics that I would have liked to address but was unable to do so given time and data limitations. First is the addition of choice model using various light sources to understand the fuels households would migrate to if kerosene becomes less available but there remains latent demand. Such assessments have been explored for residential cooking fuels (*36, 56*), but require substantial information on the cost and performance of alternative sources for the same energy service. Such information is limited for lighting. Also, an expansion of alternate scenarios to consider aspects of pro-poor growth as well as payment schemes to spread out the upfront cost of more efficient solar light technology.

Results from **Chapter 4** also highlighted the potential importance of electricity reliability and the role of secondary use on both fuel demand and impacts. I hope to expand this research to better understand the role of secondary fuel use, not only for lighting but also for other household energy issues, such as cooking and heating. Developing interventions and strategies to directly address secondary user populations will become increasingly important, I believe. Better accounting for secondary populations in impact models addressing household energy will help provide more realistic bounds to estimates, and perhaps contribute to informing more effective interventions.

Many household energy studies to-date focus on a single activity (e.g., cooking, heating, lighting), while very few have attempted to understand how these individual activities influence one another. As a longer-term goal for future work, I hope to broaden my view of household energy in order to identify potential synergies between energy- and health-improvement programs that are often implemented separately. Barriers to clean household energy can be multifaceted as well, combining social, economic and technological challenges.

5.3 Concluding Remarks

Kerosene is a highly flexible and robust fuel, making it an attractive residential energy source in low- and middle-income countries. A growing body of evidence, however, suggests that impacts of its use for household activities may pose greater risk than were once assumed and may not be appreciably better than solid fuels in several respects. Many factors contributed to a long delay in our identification of kerosene as a potentially important household risk factor, including a limited understanding of its use as a lighting fuel and, perhaps limitations in exposure classification and use of markers of complex pollutant mixtures. The current state of kerosene as a household fuel is predicated on numerous upstream drivers. Well-intentioned government subsidies on kerosene, for example, are now understood to have limited benefits, yet their presence enables continued consumption while potentially slowing progress towards better alternatives. The multi-dimensional impacts of residential kerosene use, combined with the fact that it is an inferior fuel source for any household activity, given currently available technology, suggests that shifting financial support away from kerosene towards cleaner options would be a “no regrets” option.

5.4 References

1. N. L. Lam, Y. Chen, C. Weyant, C. Venkataraman, P. Sadavarte, M. A. Johnson, K. R. Smith, B. T. Brem, J. Arineitwe, J. E. Ellis *et al.*, Household Light Makes Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps. *Environmental Science & Technology* **46**, 13531-13538 (2012).
2. S. Schare, K. R. Smith, Particulate emission rates of simple kerosene lamps. *Energy for Sustainable Development* **2**, 32-35 (1995).
3. C. Fan, J. Zhang, Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures. *Atmos. Environ.* **35**, 1281-1290 (2001).
4. J. Apple, R. Vicente, A. Yarberry, N. Lohse, E. Mills, A. Jacobson, D. Poppendieck, Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air* **20**, 399-411 (2010).
5. G. Shen, S. Tao, S. Wei, Y. Zhang, R. Wang, B. Wang, W. Li, H. Shen, Y. Huang, Y. Yang *et al.*, Retene emission from residential solid fuels in China and evaluation of retene as a unique marker for soft wood combustion. *Environmental science & technology* **46**, 4666-4672 (2012).
6. B. V. Shenoy, "Lessons learned from attempts to reform India's kerosene subsidy," (International Institute for Sustainable Development (IIST), Geneva, Switzerland, 2010).

6.0 Appendices

6.1 Appendix: Chapter 1

6.1.1 Basic Emission Rate Comparison & Exposure Equivalents

6.1.1.1 Emission Rates

The following is a basic comparison of the difference in emission rates between a kerosene wick lamp and wood stove.

Emission Rate: Wood Stove
Burn Rate: 2 kg/day (approximated)
Emission Factor: 4 $gPM_{2.5}$/kg wood (Approximated based on published values)

$$ER_{Stove} = 2\left(\frac{kg}{day}\right) \times 4.0\left(\frac{gPM2.5}{kg\_wood}\right) = 8\left(\frac{gPM2.5}{day}\right)$$

Emission Rate: Simple Wick Kerosene Lamp
Burn Rate: 0.020 kg/day
Emission Factor: 10 $gPM_{2.5}$/kg kerosene (Schare and Smith, 1995); 70 $gPM_{2.5}$/kg kerosene (Lam et al. 2012)

$$ER_{simple\_wick} = 0.020\left(\frac{kg}{day}\right) \times 10\left(\frac{gPM2.5}{kg}\right) = 0.2\left(\frac{gPM2.5}{day}\right) \text{(Based on Schare and Smith, 1995)}$$

$$ER_{simple\_wick} = 0.020\left(\frac{kg}{day}\right) \times 70\left(\frac{gPM2.5}{kg}\right) = 1.4\left(\frac{gPM2.5}{day}\right) \text{(Based on Lam et al. 2012)}$$

Comparison

$$Emission\_Ratio_{stove-sw} = \frac{ER_{stove}}{ER_{simple\_wick}}$$

$$Emission\_Ratio_{stove-sw} = 40 \quad \text{(Based on Schare and Smith, 1995)}$$
$$Emission\_Ratio_{stove-sw} = 6 \quad \text{(Based on Lam et al. 2012)}$$

6.1.1.2 Exposure Equivalents

This example approximates the equivalent exposure time required for a lamp user to receive an equal exposure to $PM_{2.5}$ as an open fire (stove) user.

Environmental Parameter Assumptions:
Air exchange rate (α): 8/hr (Estimated based on pilot experiments)

Room Volume (V): 40 cubic meters (Estimated)

Pollutant Emission Parameters
Burn Rate, kg fuel/hr (BR): 1.0 (stove); 0.009 (simple wick lamp - Apple et al. 2010)
Emission Factor, $gPM_{2.5}$/kg fuel (EF): 3.2 (stove); 80 (simple wick)

Given the environmental parameter assumptions, the theoretical stead state pollutant concentration is achieved between 15-17 minutes. Exposure times are on the order of hours and substantially larger than the time to steady state. Thus, we apply a simplifying assumption for illustrative purposes and describe the room concentration at steady state:

$$C_{ss} = \frac{G}{\alpha V} = \frac{BR \times EF}{\alpha V}$$

Estimates at Steady State Concentrations (C_{ss})

$$C_{Stove} = (1.0 \times 3.2)/(8 \times 40) = 10 mg/m^3$$
$$C_{Lamp} = (0.009 \times 80)/(8 \times 40) = 2.3 mg/m^3$$

Both concentrations are within a reasonable range of concentrations observed in homes during cooking and lighting events.

$$\frac{C_{Stove}}{C_{Lamp}} = \frac{10}{2.3} = 4.3$$

To receive equivalent exposures, a lamp user would require an exposure duration that is approximately 4 times greater than the stove exposure duration. If we assume that a person cooks 2-3-hrs per day, the duration of lamp exposure required for an equivalent cumulative exposure is approximately 8-12 hrs.

6.2 Appendix: Chapter 2

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6.3 Appendix: Chapter 3

6.3.1 Duplicate Measures

Duplicate and triplicate measurements were collected in all experiments for XAD tubes and actively sampled XAD filters. Strong agreement between simultaneously collected measures can be indicative of several measurement characteristics that add validity to final estimates. From a field collection standpoint, it indicates that bias from in-field measures which factor into final concentrations are adding little variability (e.g. flow rates, slightly different location of the duplicate sample, handling). From a laboratory standpoint, it suggests that factors influencing sample media or analytical procedures are factoring little into variability (e.g. sample extraction, filter coating). It is important to note, however, that comparisons provide an indication of non-systemic factors affecting precision, but may not be indicative of accuracy.

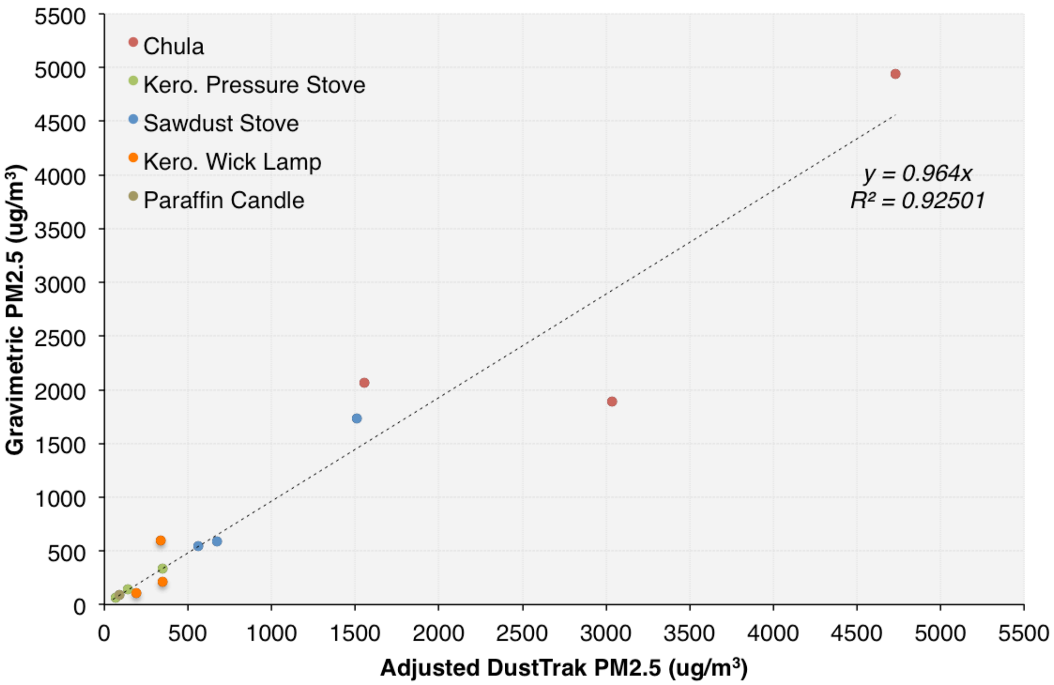


Figure 6.3.1. Scatterplot of gravimetrically measured $PM_{2.5}$ concentrations versus DustTrak $PM_{2.5}$ mass concentrations (light scattering) after device (aerosol) specific adjustment.

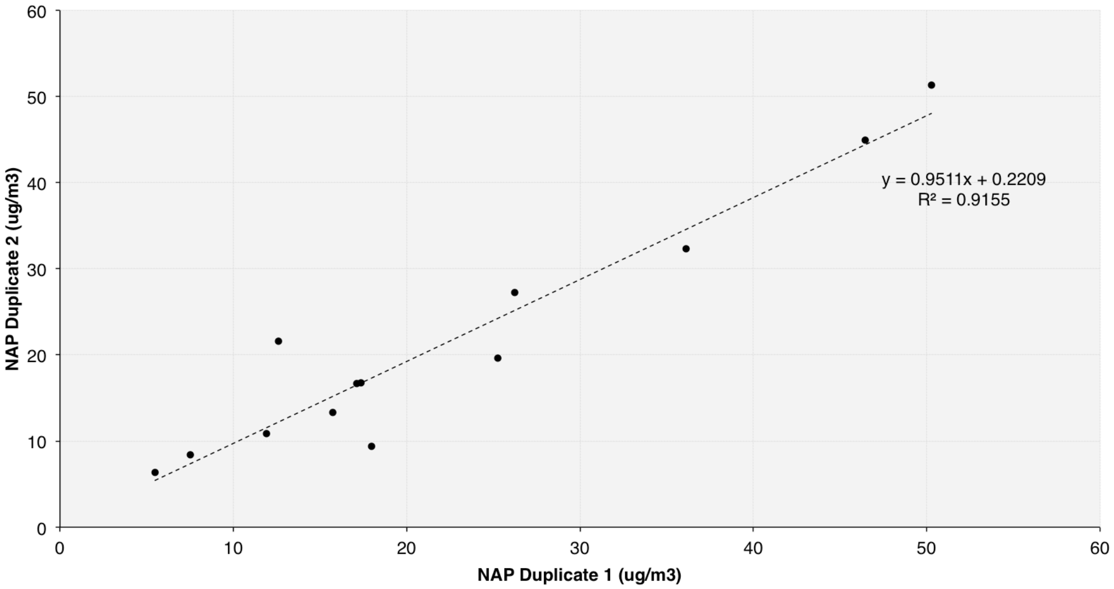


Figure 6.3.2. Duplicate measures of naphthalene concentrations based on XAD tube samples. Dashed lined represents the line of best fit based on ordinary least squares regression

6.3.2 PAH/PM$_{2.5}$ Ratios

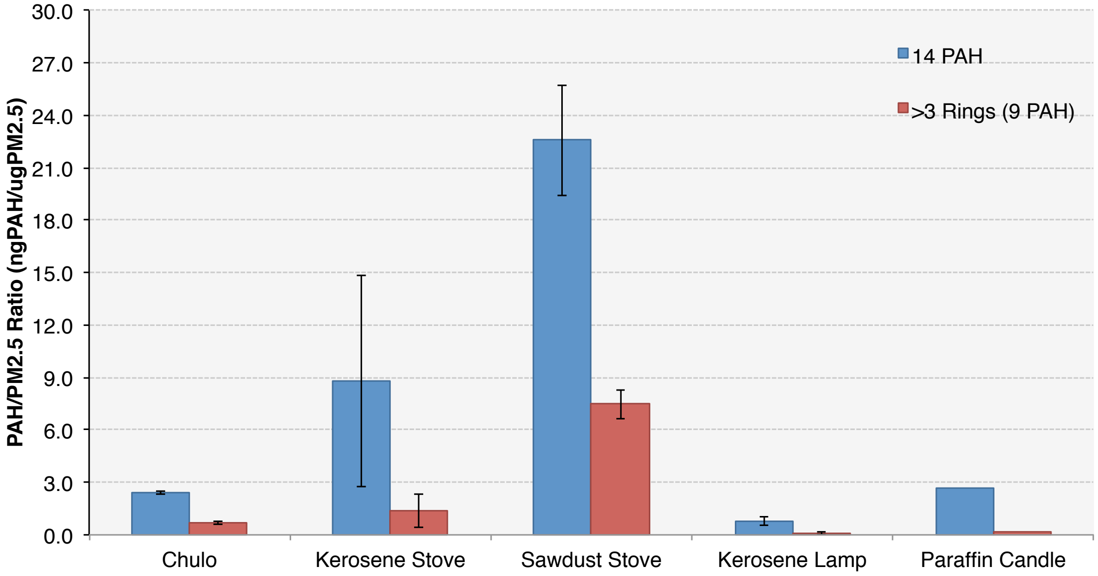


Figure 6.3.3. Ratios of average PAH (ng/m^3) concentrations versus PM$_{2.5}$ (μg/m^3), using the full set of 14 PAH measured from XAD impregnated filters and only those greater composed of more than three benzene rings. The height of the columns corresponds to the average of two experiments bar ends correspond to ratio values of the two experiments. Only one experiment of the paraffin candle was conducted with PAH media.

6.4 Appendix: Chapter 4

6.4.1 Introduction

6.4.1.1 Kerosene Subsidies in India

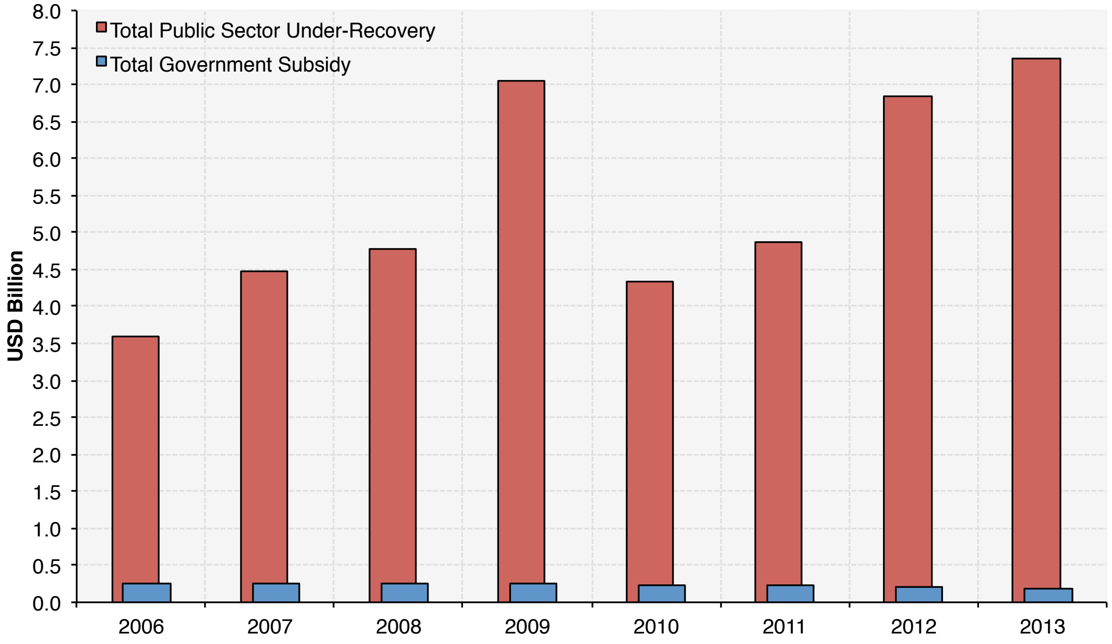


Figure 6.4.1.1. Annual government kerosene subsidies and public sector under recoveries (USD) in India 2006 to mid 2013. Source: Petroleum Planning and Analysis Cell (PPAC), summarized in (*1*)

6.4.2 Methods

6.4.2.1 Household Survey & Population Grouping

6.4.2.1.1 Household Survey

Household energy characteristics and trends were obtained from an analysis of the India Human Development Survey (IHDS) 2005 (*2*). IHDS is a nationally representative, multi-topic survey of 41,554 households covering 1,503 villages and 971 urban neighborhoods across India. The working survey size used for analysis was 34,119 after removing households with incomplete expenditure data on any of the measured household fuels. IHDS consists of six components with residential energy characteristics measured in the Individual Survey and Household Survey. IHDS was selected for this study over other available surveys because the design of energy questions yielded added information for identifying secondary demand of kerosene for lighting and electricity supply reliability. As opposed to querying for primary energy sources by activity, IHDS collects information on the consumption and expenditure of different fuels and identifies a main end-use activity for each (including not used). This method still relies on self-reported information and thus is not a purely objective measure, but it does require fewer assumptions for defining between primary and secondary usage. The added information also reduces ambiguity in identifying a single "primary" energy source for activities like cooking and lighting that may be prone to energy stacking (*3*). The benefits of designing energy surveys in this way will vary by fuel and study goals, but was important in the context of this study because kerosene has multiple end-use activities (e.g. cooking, lighting, heating) with different emission characteristics.

6.4.2.1.2 Population Groupings

To facilitate analysis, the population was disaggregated into three hierarchical levels yielding a total of thirteen analysis groups (**Figure 6.4.2.1**). Urban and rural sectors were disaggregated into five per-capita expenditure groups: two urban (<2.00, ≥2.00 $/day) and three rural (<1.25, 1.25-2.00, ≥2.00 $/day). Within each expenditure group, a further distinction was made between households with no access to electricity, less than 16 hours of supply per day (low reliability), and ≥ 16 hrs/day (high reliability). Prevalence of electricity exceeded 95% in urban areas so only the latter two access groups were distinguished with non-electrified homes combined with the lowest access group. Expenditure cutoffs were selected for comparability, but were also selected to provide a reasonable balance of samples across groups.

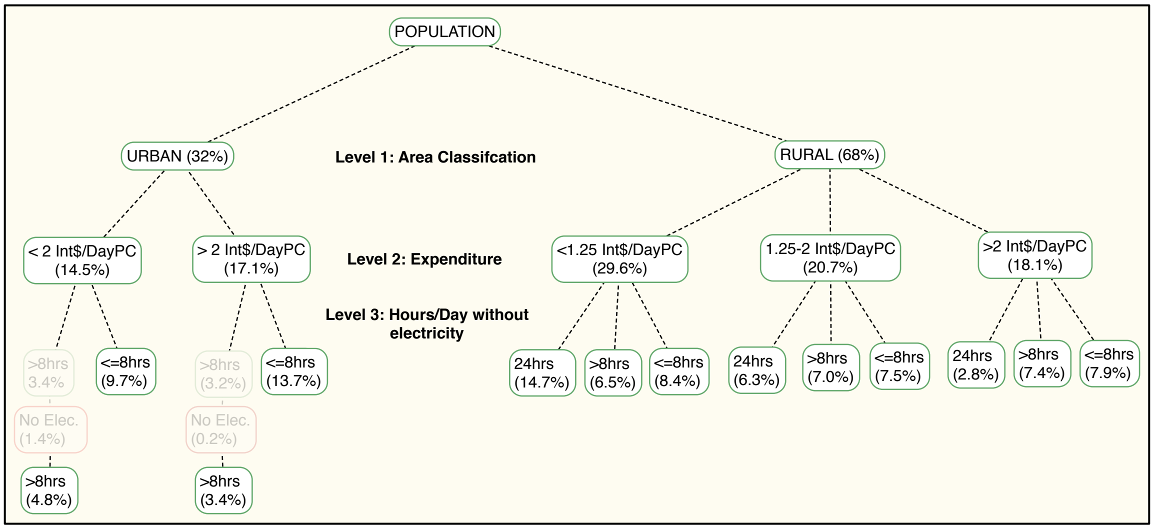


Figure 6.4.2.1. Hierarchical breakdown of population based on (1) area classification, (2) per-capita household expenditure (income proxy) and (3) electricity supply/access: **Level 1.** Area classification: Urban or Rural; **Level 2.** Per-capita household expenditure (expenditure level): 5 categories (2 urban and 3 rural); **Level 3**. Electricity supply (supply level): 13 categories (4 urban, 9 rural).

6.4.2.2 Kerosene Lighting Characteristics

6.4.2.2.1 Primary and Backup/Secondary Kerosene Lighting

Kerosene end-use activities are measured in the IHDS Individual Survey, while the Household Survey provides a more detailed accounting of kerosene purchasing sources and unit costs. End-use is measured categorically and reported as either not being used, or used for mainly cooking, mainly lighting, mainly heating or an undefined combination. Existing studies and reports indicate that residential kerosene is most often used for lighting, cooking, or a combination of the two (*4-6*).

If kerosene was reported as being used mainly for a single activity, for the purposes of this study, all fuel was allocated to that activity. Combination use was reported by approximately 15% of kerosene using households. In these instances, the fraction of kerosene used for lighting was estimated by first assuming that combination activities were limited to cooking and lighting, heating being negligible. Among non-combination users, less than 2% reported use for mainly heating, confirming it as a minor activity. To estimate lighting consumption, we take advantage of trends from "mainly lighting" users. Reported volumetric consumption of kerosene was regressed on household per-capita expenditure separately for each electricity supply group. Relationships were estimated separately for urban and rural areas over the five electricity supply groups (2 urban, 3 rural) defined in **Section 4.2.1.2**. Estimated lighting consumption was then compared to reported consumption and any remaining kerosene was allocated to cooking. If estimated kerosene for lighting exceeded the quantity reported, all kerosene was allocated to lighting. The inclusion of combination users altered mean consumption estimates for cooking and lighting activities by less than 10%.

6.4.2.2.2 Service Metrics

Expressing kerosene consumption in the form of a service metric is useful for contextualizing the utility it provides to a house, while at the same time accounting for heterogeneity in technology costs and efficiencies. Most analyses presented here are reported in the service metric of *light-hrs*, the hours of lighting provided, as opposed to the more common metric of *lumen-hrs*, which is an extension of *light-hrs* that accounts from the lumen efficiency (brightness) of the source. The choice of service metric has no influence on the consumption estimates underlying it, however, but may so if evaluating energy choice or willingness to pay, since it makes an implicit assumptions about how light service is valued.

6.4.2.3 Alternate Scenarios

The *(a) Baseline* scenario assumes that no measures are taken to increase electricity access or improve supply over time beyond changes associated with growing household income. The *(b) Universal Connection (UC)* scenario assumes that all households receive a connection to electricity by 2030, but no additional efforts are made to improve supply reliability. Electricity connection growth is assumed to be linear between 2005 and 2030, resulting in a growth rate of approximately 1.4% per year. The *(c) Universal Connection and Supply Improvements (UCS)* scenario complements the universal access scenario by assuming improvements to electricity supply are coupled with improved supply, such that all households have at least 16 hours of supply per day. Growth is assumed to be linear between 2005 and 2030, resulting in an annual growth rate (low access to highest access) of 2.2%.

Two additional scenarios are used to evaluate the effect of changes to kerosene price and reflect changes to economic access: The *(d) Subsidy Phase-out (SPO)* scenario assumes a linear phase-out of the subsidy such that all households are faced with the future market price of kerosene by 2030. Growing international pressure and associated costs with long-standing kerosene subsidies in India and other developing countries have prompted considerable discussion to reduce or entirely remove them in the near future. Conversely, the *(e) Full Subsidy Scenario* (*SF*) assumes all homes are given access to kerosene at subsidy prices after the base year. This scenario is meant as a bounding scenario for illustration and is not necessarily a realistic option given the current opinions on fuel subsidies or the viability of discounting such a massive quantity of fuel. Both price scenarios assume the Baseline trajectory for electricity connection and reliability growth.

Finally, an *Interim Household Technology* (*Solar*) scenario reflects a condition in which kerosene use for light is gradually replaced with alternate technology with equal or greater lighting service. This scenario assumes kerosene used for lighting (primary and secondary houses) is replaced with solar technology by 20% in 2015 to 100% by 2030. For cost estimates, we define this technology as entry-level pico-solar lighting devices, approximately equivalent in price and performance to those certified under the Lighting Global Minimum Quality Standards (*7*). Several options for providing light in place of kerosene exist, however. Electrification with village-level micro-grids, for example, could meet lighting needs as well as provide energy for many other services (e.g. refrigeration, businesses etc.). Pico-solar LEDs were selected as an interim solution for several reasons: they are immediately available, directly address lighting services, perform independent of any community or other central grid system, could potentially leverage current distribution infrastructure in place for subsidized fuels, and are close to being financially accessible to all houses ($20-30 per device). Over the past two decades, more than 1.6 million solar home lights and solar lanterns were installed in India based on the Ministry of New and Renewable Energy, Govt. of India, New Delhi.

6.4.2.4 Future Demand For Lighting Kerosene

Future per-capita demand for lighting kerosene is estimated using cross-sectional trends observed across geographic sectors (rural/urban), expenditure and electricity service groups. To the extent possible, future consumption accounts for changes and feedbacks from shifts in future population growth, household expenditure (**6.4.2.4.1**), and fuel price (**6.4.2.4.2**). Demand for kerosene in the future is modeled as a function of two main grouping variables: per-capita household expenditure (income) and electricity service level. The effect of fuel price on demand is accounted for using demand (consumption) curves derived form an analysis of IHDS. In several instances, methodologies benefitted and were informed by procedures developed for the Global Energy Assessment (*8, 9*).

6.4.2.4.1 Household Expenditure Dynamics

Future GDP projections are used as a proxy for household income (expenditure) growth in future evaluation years. Future projections of national GDP and population growth developed for the 2013 GEA (*10*) are combined with income share statistics estimated by the World Bank World Development Index (2008). The quantity of GDP associated with an individual in quintile group (*h)* in year *t* is estimated as:

$$GDP_{h,t}(\$/PC) = \frac{GDP_t^{Total} \cdot f_q^{income}}{0.2 \cdot Pop_t^{Total}}$$

Where GDP is the projected national GDP in India in year *t (11)*, *f* is the percentage share of income by population quintile, *q*, and *Pop* is the total population in year *t* multiplied by 0.2 to reflect a fifth of the population. Expenditure distributions in all but the highest expenditure groups were kept static over time (*12*). Inherent in the dynamics used to project income growth are several assumptions: Changes in income are proportional to expenditure, changes in GDP are a reasonable proxy for changes in household expenditure, and income fractions are fixed over time, that is, GINI coefficients are fixed at 2008 levels. Future efforts should consider assumptions that reflect conditions with pro-poor growth, but this is not explored in depth in this first assessment. For modeling per-capita expenditure growth in the future, expenditure distributions in all but the highest expenditure levels were kept static over time (See **Section 6.4.2.4.3**). **Figure 6.4.2.2** illustrates population dynamics over rural analysis groups to 2030 under the Baseline Scenario.

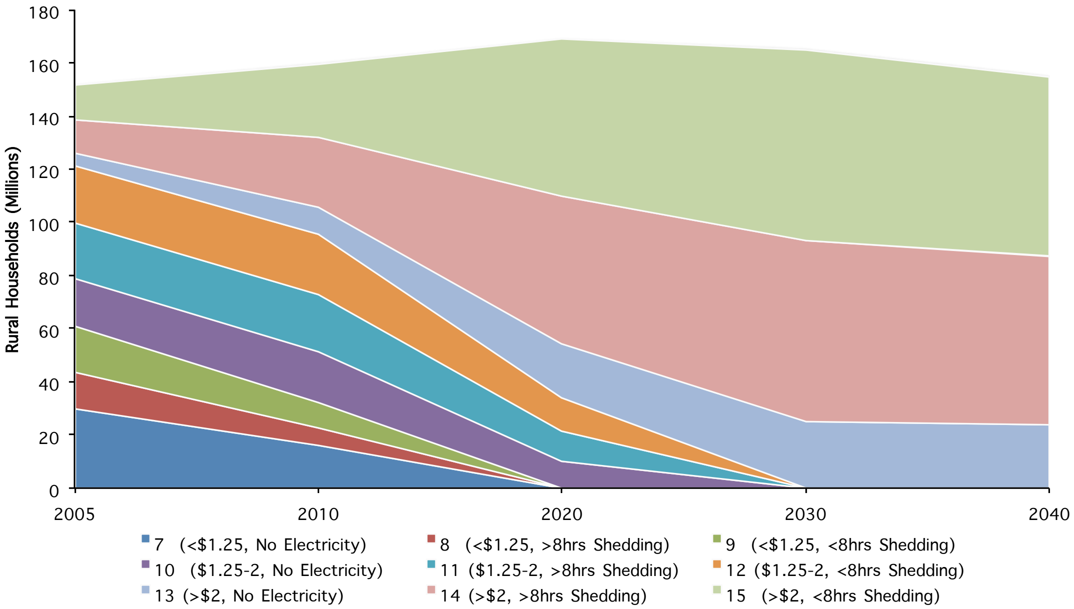


Figure 6.4.2.2 Illustration of projected population shifts over rural analysis groups under the Baseline scenario

6.4.2.4.2 Kerosene Lighting Device Stock

Kerosene used for residential lighting is consumed by devices that can be categorized into three broad groups: simple wick lamps, hurricane/glass table lamps, and pressurized mantle lamps (Petromax). Simple wick lamps are the least expensive, most polluting, and least efficient at generating light (approximately 10-20 lumens). Hurricane/table lamps are cleaner and generate more light (20-30 lumens), but consume fuel at a slightly faster rate. Petromax lanterns generate the most light (400 lumens) and are the least polluting, but consume fuel at a high enough rate to be prohibitively expensive for much of the kerosene using population. Lighting device performance characteristics are presented in **Table 6.4.2.1** and based on published and grey literature (*13-16*).

Table 6.4.2.1 Kerosene lighting device performance characteristics

Light Source	Estimated Stock 2005	Light Hour Efficiency	Lumen Efficiency	Capital Cost	Lifetime
	%	Light-hr/Liter	Lumen-hr/Liter	2005$	Years
Simple Wick	51%	80	830	1.5	2
Hurricane/Table	48%	65	1670	3	3.5
Petromax/Pressure	1%	10	4350	25	5

IHDS does not collect information on lighting devices used by households, so the proportion that each device constitutes of total lighting stock is informed by available literature and reports (*4, 13-15, 17, 18*). Since the ability to purchase lighting devices and consume fuel is limited by income, the proportion of each device type is determined at the expenditure group level. To determine the proportional change over expenditure groups, I assume a linear reduction in simple wicks (least expensive but most polluting) with increasing expenditure, which is compensated by an increase in hurricane and pressurized lanterns. For scenarios shown here, the national stock profile is 51% simple wick, 48% and 1% pressure. The UNEP En.lighten initiative, for example, has estimated simple wick stock at approximately 35-40% (*15*). We assume no difference between urban and rural stock profiles given the same expenditure level. **Figure 6.4.2.3** shows the percent of kerosene lighting device stock over expenditure.

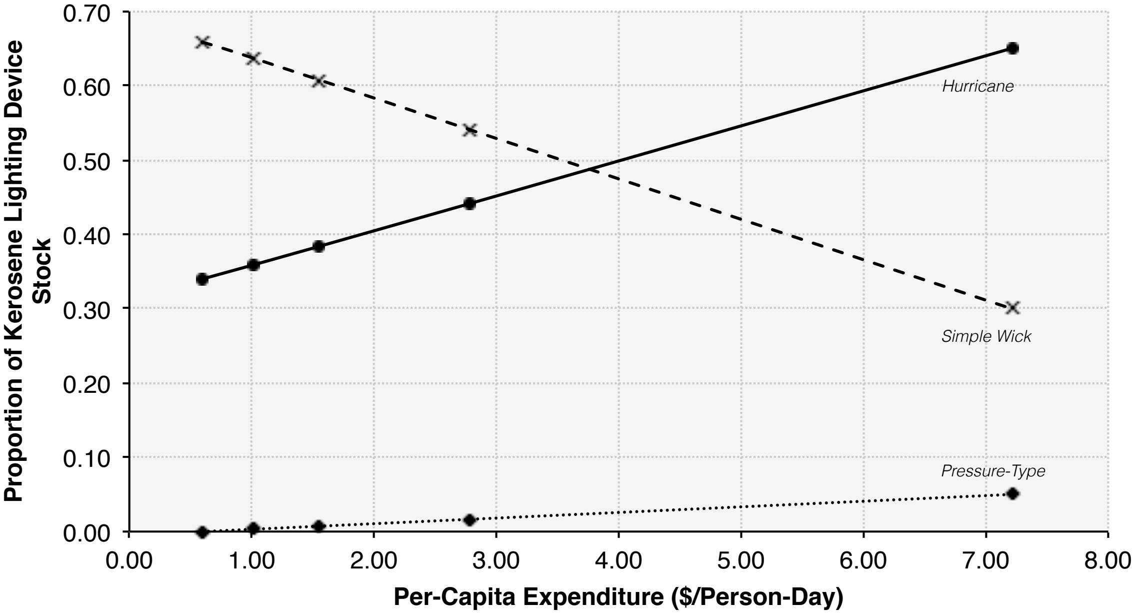


Figure 6.4.2.3 Kerosene device stock percentage assumptions over expenditure groups

6.4.2.4.3 Fuel Price

Future changes in the market price of kerosene were accounted for using the non-linear macroeconomic model MACRO embedded within the energy system model MESSAGE (*19*) and its counterpart for residential energy assessment MESSAGE-Access (*9, 20*). The linkage with the larger MESSAGE energy system model allows for residential energy use to be influenced by macro feedbacks from the larger energy system, particularly via energy prices.

Kerosene in MESSAGE is not differentiated from other light-oil (e.g. Diesel), and thus constitutes only a small percentage of the overall demand of global light-oils. Furthermore, since this study only evaluated demand changes for India, the global fuel price is affected negligibly by alterations to kerosene lighting demand. Nevertheless, for consistency, demand was iterated with MESSAGE until convergence, which was achieved in all scenarios in two steps, the minimum iterations required.

In converting MESSAGE shadow prices to population prices I assume that future changes in price are carried to the consumer. For subsidized kerosene, this assumption implies that the subsidy price of kerosene in future years changes from the 2005 level in proportion with the global market price. In the subsidy phase-out scenario, the PDS price of kerosene is incrementally increased until 2030 when the market and PDS prices become equal. For example, under a linear removal of the subsidy from 2005 to 2030, the population average price of subsidized kerosene will increase by approximately 2% each year until 2030. The absolute value added to the PDS price changes over time, however, since the market price is also changing as a result of macro-level shifts in fuel pricing.

6.4.2.4.4 Effect of Fuel Price on Demand

The effect of future fuel price on kerosene demand was estimated using cross-sectional consumption (demand) curves. Separate curves were estimated for all 13 electricity supply groups using a regression of service (e.g. light hours) on service cost (e.g. $/light-hr). Fuel prices and consumption quantities were available from IHDS, while investment costs and performance information of kerosene lighting devices were informed by existing studies (See sub-sections within **6.4.2.4.1**) and amortized using income specific implicit discount rates for India (see subsequent sub-sections).

The effect of income growth on per-capita kerosene demand for light in the future is adjusted for using cross-sectional trends from the base year. This is done separately for urban and rural populations over each electricity supply group for a total of five dynamic groups. Associations between total expenditure and consumption of kerosene for light are described in the main text and **Section 6.4.3.2**. Generally, however, increased household expenditure was positively associated with consumption of kerosene for light, while the service level of electricity modified this relationship. **Figure 6.4.2.4** illustrates the effect of adjusting for income growth on consumption (no adjustment for fuel price).

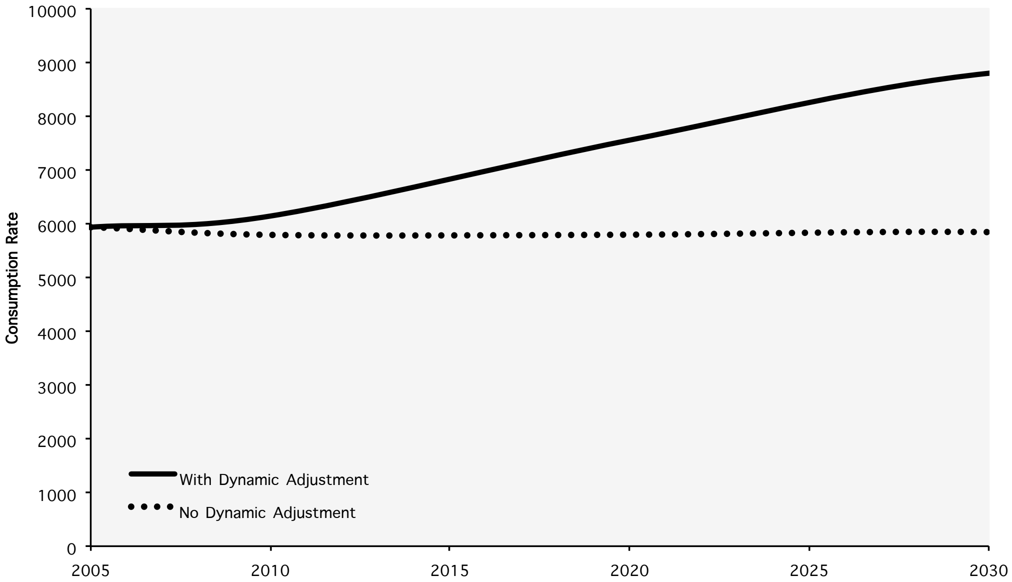


Figure 6.4.2.4. Example scenario illustrating total consumption with and without adjustment for dynamic economic growth in the highest expenditure groups in future years.

6.4.2.4.4.1 Service Cost of Kerosene Lighting

The service cost of lighting is the economic cost per unit of lighting service, as measured in either *light-hrs* or *lumen-hrs*. The economic cost encompasses operating costs, largely dominated by fuel, and the annualized investment cost of lighting devices adjusting for household-level implicit discount rates (IDR). Expenditure on kerosene for lighting is measured as part of IHDS. To calculate investment cost, the number of lighting devices was estimated using an estimate 0.4 and 0.6 lamps/person in urban and rural areas, respectivley.

Lighting device costs were annualized using implicit discount rates specific to populations in India. IDR values were estimated from the empirical relationship reported in Eckholm et al. (2010) and updated by Nagai (2013) (*20, 21*):

$$IDR_i = -0.162 \times \ln(Exp_i) + 1.956$$

Where *Exp* is the annual expenditure of the household in 2005 USD, including imputed biomass. Eckholm et al. (2010) note that the empirical discount rates for households in India, and other developing country households for that matter, are significantly higher than the default value of around 5% typically assumed in energy assessments for developed country households. Electricity service group-level average IDRs calculated for homes in this study ranged from 47- 73% in urban populations and 48 – 81% in rural populations, which is consistent with findings in Eckholm (2010).

6.4.2.4.4.2 Price Sensitivity

There exists some evidence that demand for individual residential fuels in developing countries is highly sensitive to price (*9, 21*). No study to date, however, has specifically focused on measuring the sensitivity of demand for kerosene as a lighting fuel.

Kerosene service and service costs were used to estimate demand curves for each of the 13 electricity supply groups. Estimated group level demand functions describe how changes in the service cost of kerosene lighting among using households shifts the average service demanded by an average house in the group. This service demand can then be transformed to a fuel metric using lighting device efficiencies. Demand curves were used in this study to estimate how price changes to kerosene in the future, based on fuel prices estimated from MESSAGE, affect the demand of kerosene in each electricity supply group and the general population.

For each of the 13 supply groups, the demand curve followed an inverse power function (constant elasticity), which was then linearly transformed, and regressed using survey weighted ordinary least squares regression to predict a line of best fit. In the process of linearizing the inverse power function, the contribution of non-kerosene lighting users is lost, since the log of their service demand of zero is undefined. To re-scale the service axis to be representative of the average house in the group population, the service demand of users was multiplied by the percentage of kerosene lighting users in each group.

Demand for kerosene used for lighting was highly elastic indicating a high sensitivity to price. Demand curves are illustrated in **Figure 6.4.2.5a-b** with corresponding coefficients from the log-log regression of service price on service level in **Table 6.4.2.2.** Although visual depictions of demand are represented using this configuration, demand elasticity is technically a regression of service on service price. Results from **Table 6.4.2.2** correspond to demand elasticity values ranging from -2 to -6.

Table 6.4.2.2. Coefficient estimates from a regression of logged service price ($/light-hour) on logged service (light-hr) by electricity service groups to reflect the traditional depiction of the demand curve (**Figure 6.4.2.5a-b**). Values in parentheses correspond the 95% CI.

		β_1	**βo**	**R-Squared.**
< $2.00	< 16	-0.17 (-0.27, -0.08)	-3.65	0.55
	> 16	-0.20 (-0.26, -0.13)	-3.85	0.66
> $2.00	< 16	-0.15 (-0.26, -0.03)	-3.56	0.30
	> 16	-0.20 (-0.26, -0.13)	-3.74	0.67
< $1.25	No Electricity	-0.08 (-0.14, -0.03)	-4.12	0.49
	< 16	-0.09 (-0.17, -0.01)	-4.17	0.35
	> 16	-0.20 (-0.27, -0.12)	-4.06	0.65
$1.25-2.00	No Electricity	-0.04 (-0.11, 0.03)	-4.13	0.12
	< 16	-0.10 (-0.17, -0.04)	-4.10	0.45
	> 16	-0.20 (-0.27, -0.12)	-4.06	0.65
>$2.00	No Electricity	-0.06 (-0.11, -0.02)	-3.97	0.43
	< 16	-0.08 (-0.17, 0.01)	-3.99	0.20
	> 16	-0.17 (-0.23, -0.11)	-3.95	0.74

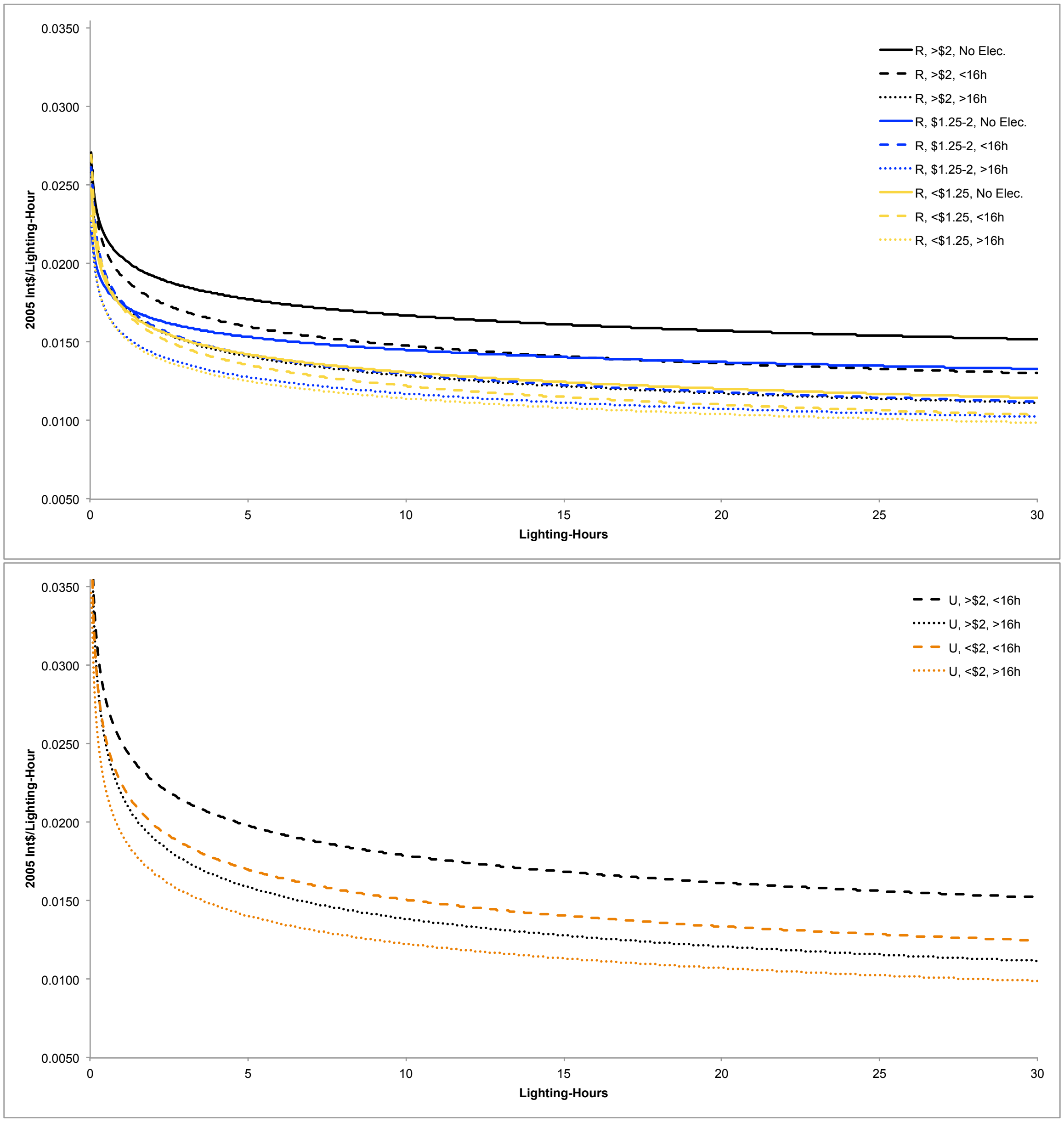


Figure 6.4.2.5a-b. Estimated kerosene lighting demand (consumption) curves for rural (top) and urban (bottom) electricity supply groups.

6.4.2.5 <u>Impacts</u>

6.4.2.5.1 Emissions and Outdoor Air Quality Impacts

The Greenhouse gas – Air pollution Interaction and Synergies (GAINS) model is an integrated assessment model designed to assess the costs and potential for air pollution and greenhouse pollutant mitigation strategies. Estimates of emissions, subsequent impacts on outdoor air quality, health and associated mitigation costs must first begin with underlying emission inventories. Thus, a critical component of this project was adding domestic lighting as a separate activity in GAINS inventories for South Asia and India specifically. Kerosene lighting consumption based on IHDS was combined with estimated device stock (**Section 6.4.2.4.2**) and emission factors informed by existing literature (*16*).

6.4.2.5.1.1 Estimating Years of Life Lost from Primary $PM_{2.5}$ Outdoor Exposure

The GAINS model quantifies for different emission scenarios premature mortality (years of life lost, YLL or YOLL) that can be attributed to long-term exposure to $PM_{2.5}$, following the outcomes of the American Cancer Society cohort study by Pope et al. 2002 (*22*) and its re-analysis (*23*). This methodology is described in detail within Amann et al. (2011) and summarized here (*24*). GAINS currently does not consider loss of life due to disability (years lost to disability, YLD)

Cohort and country-specific mortality data extracted from life table statistics are used to calculate the baseline survival function for each cohort over time (*24*). The survival function $l_c(t)$ indicates the percentage of a cohort, c, alive after time t elapsed since starting time w_0. $l_c(t)$ is an exponential function of the sum of the mortality rates $\grave{\imath}_{a,b}$, which are derived from life tables with a as age and b as calendar time. As the relative risk function taken from Pope et al. (2002) applies only to cohorts that are at least $w_0 = 30$ years old, younger cohorts were excluded from this analysis. That is, health impacts for people younger than 30 years, and in particular the impacts on infant mortality, are presently not considered in GAINS. Therefore, for a cohort aged c, $l_c(t)$ can be estimated as:

$$l_c(t) = exp\left(-\sum_{z=c}^{t} \mu_{z,z-c+w_0}\right) \tag{1}$$

The survival function is modified by the exposure to PM pollution, which changes the mortality rate and consequently the remaining life expectancy (e_c). For a given exposure to $PM_{2.5}$, life expectancy $\overline{l_c}$ is calculated as the integral over the remaining life time:

$$e_c = \int_{c}^{w_1} \overline{l_c}(t)dt = \int_{c}^{w_1} \exp\left(-RR_{PM} \sum_{z=c}^{t} \mu_{z,z-c+w_0}\right)dt \tag{2}$$

where w_1 is the maximum age considered and RR_{PM} *is* the relative risk at a given concentration of $PM_{2.5}$ (*PM*). With some simplifying assumptions and approximations (*25*), the change in life expectancy per person (Δe_c) of a cohort c can be expressed as:

$$\Delta e_c = \beta PM \int_{c}^{w_i} l_c(t)\log l_c(t)\,dt \tag{3}$$

within the studied exposure range, RR_{PM} has been approximated as $RR_{PM} = \beta \cdot PM + 1$ with $\beta = 0.006$ as given in Pope et al. (2002). For all cohorts in a country l the change in life years, ΔL_l, is then calculated in GAINS as the sum of the change in life years for the cohorts living in the grid cells j of the country l (which is only India here):

$$\Delta L_l = \sum_{c=w_0}^{w_1} \Delta L_{c,i} = \beta \sum_{j \in l} PM_j \frac{Pop_j}{Pop_l} \sum_{c=w_o}^{w_1} l_c(t) log l_c(t) dt \tag{4}$$

where $\Delta L_{c,l}$ is the change in life years lived for cohort c in country l, $Pop_{c,l}$ is the population in cohort c in country l, Pop_j is the total population in grid cell j (at least of age $w_0 = 30$), and Pop_l is the total population in country l (at least of age $w_0 = 30$).

For the health impact assessment of policy scenarios, GAINS calculates the loss in statistical life expectancy according to Equation (3) as well as the total amount of life years lost for the entire population over 30 years.

6.4.2.5.1.2 $PM_{2.5}$ Control Costs: Pico-Solar LED

Survey information on use of kerosene for light combined with emissions characteristics was used to inform an exploratory estimate of control cost of primary $PM_{2.5}$ using household-level light devices. Previously, I have assumed the "Solar" or "Interim Tech by 2030" scenario as being any technology not reliant on the growth of electrification services. For exploring control costs, the replacement technology explored are pico-solar LED lanterns, currently being promoted as part of the Lighting Global initiative (http://www.lightingglobal.org), among others. These devices are approved using quality assurance testing protocols developing by Lighting Global, and cost approximately 25-50 USD per device in stores for entry-level lamp. Almost all have multi-year warranties on the battery and PV cell and in some cases can be used to charge mobile phones. The baseline technology is assumed to be the simple wick lamp or hurricane lamp.

Emission controls costs can be divided into investment (lamp), fixed operating (e.g. wicks, lamp shielding) and variable operating (e.g. fuel) costs components. From this, the annual cost per unit of activity level is calculated relative to the Baseline technology and related to a pollutant emission using an average emission factor (gPM/MJ).

$$Cost_{control}\left(\frac{USD}{kgPM_{2.5}}\right)=\frac{(Cost_{Base}-Cost_{Control})}{(MJ_{base}\cdot EF_{base}-MJ_{control}\cdot EF_{control})}=\frac{(Cost_{Base}-Cost_{Control})}{(PM_{base}-PM_{control})}$$

Control costs are sensitive to various assumptions affecting components of lighting cost parameters – such as investment cost, fuel expenditure and household discount rates. As an exploratory estimate, I apply conservative estimates (in favor of kerosene technology) assuming a lower bound of annual kerosene consumption (~20 \$/HH-year), upper bound lifetime of kerosene devices (8 years versus 5 years for pico-solar) and a higher default discount rate than is assumed for energy technologies (50%). Both hurricane and pico-solar devices are assumed to have annual operating costs equivalent to 10% of the investment cost; no operating costs are assumed for simple wick lamps. Finally, comparisons do not consider differences in the quality of service (e.g. lumens) being provided to the user and costs associated with implementation potentially against (e.g. distribution infrastructure) or in favor (e.g. economy of scale effects) of solar devices.

Control costs for pico-solar lighting relative to basic kerosene technology are negative (cost savings), varying from 3 - 10 \$/kg $PM_{2.5}$, despite conservative assumptions. As an exploratory estimate, the control of implementing kerosene hurricane lanterns, which is kerosene-fueled but less polluting, is approximately 0.5-1.5 \$/kg $PM_{2.5}$.

6.4.2.5.2 Economic Impacts: Deadweight Loss

6.4.2.5.2.1 Deadweight Loss (DWL)

Subsidies in general generate deadweight loss by enabling transactions when the buyer's willingness to pay is below the opportunity cost. Deadweight loss (DWL) is a measure economic inefficiency resulting from this artificial pricing. In the context of this study, kerosene and other household fuel subsidies reduce the price observed by the consumer, allowing for greater consumption than would likely occur under a competitive market price (zero subsidy). This may, in turn, affect the competitive strength of alternative fuels or technologies depending on their cost relative to the subsidized fuel. In some instances, effects extend beyond the subsidized fuel and its immediate competitors. For example, artificially placing kerosene prices below that of diesel, which is similar in composition but higher in price, incentives diversion away from intended residential uses towards the transport sector.

The amount of DWL is a function of an individual's willingness to pay for the fuel at a given price, which is dictated by the elasticity of demand (ε_d). Based on previous studies on fossil fuel subsidies, I make the assumption that supply for fossil fuels are perfectly elastic, that is, the cost of production is constant regardless of demand level (*26*). A higher ε_d could be a result of more competing or alternative technologies and energy sources or, for poor homes, an unwillingness or inability to pay for the fuel. In the latter case, a home without electricity might reduce the hours of lighting or simply go without light. A greater elasticity of demand yields larger DWL, since it implies a stronger effect (reduction) on demand for a unit change (increase) in price.

6.4.2.5.2.2 DWL Estimation Procedure

Deadweight loss is estimated for kerosene using the method described by Davis (2014). Estimated demand curves from survey analysis were best represented by an inverse power curve across all groups based on goodness of fit (*R-squared*). This is equivalent to assuming constant demand elasticity, $q = Ap^{\varepsilon_d}$. Where q is the demand quantity at price, p, given elasticity of demand, ε_d, and random intercept A. In practice, the random intercept A and ε_d can be estimated for different groups from a linear regression of logged demand on logged utility cost. Note that this is the opposite of how demand curves are typically depicted in figures - with the price on the y-axis and demand on the x-axis. Device efficiencies and unit fuel costs can then be applied to convert from utility cost to liters and dollars, respectively.

Two approaches are used to estimate the DWL for lighting. The first method applies survey-based estimates of the components of the constant demand elasticity function. That is, we assume a demand follows an inverse power function and is different across household groups. Since larger (more negative) ε_d yield higher DWL, we apply a second simplified and more conservative approach which assumes unit elasticity, $\varepsilon_d = -1$ (percent change in price is proportional to change in demand), homogeneity elasticity across household groups, and a linear demand function.

Davis (2014) clearly outlines a procedure for estimating DWL from a constant elasticity of demand function (**Figure 6.4.2.6**). This process is outlined briefly here:

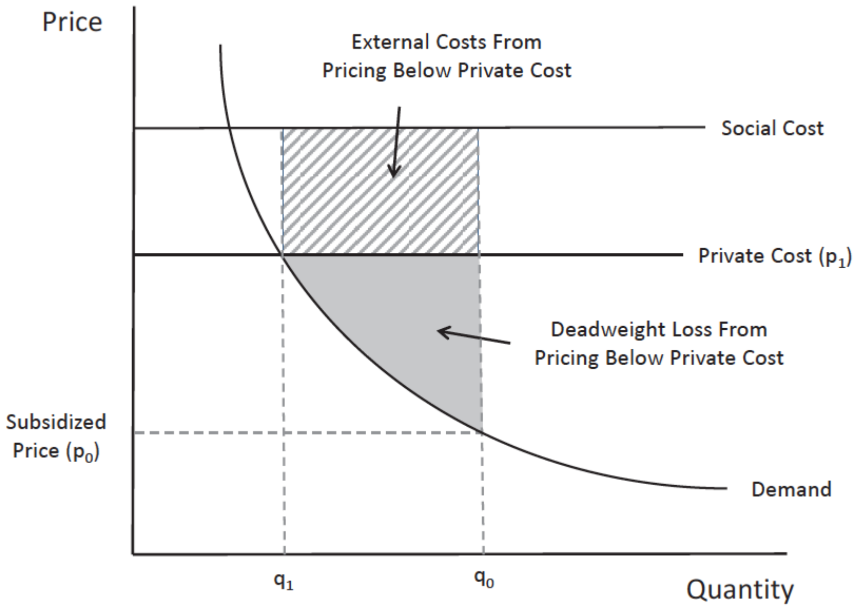


Figure 6.4.2.6. From Davis (2014): where the subscripts "0" and "1" represent the unit price, p (e.g. utility cost, fuel cost), or quantity demanded, q, under the subsidized and private (natural) cost, respectively.

The shaded region of **Figure 6.4.2.6** corresponds to the deadweight loss ("deadweight loss from pricing below private cost"), the area of which can be calculated as:

$$DWL = (p_1 - p_0)q_0 - \int_{p_0}^{p_1} Ap^{\epsilon_d}\, dp.$$

Evaluating the integral yields:

$$DWL = (p_1 - p_0)q_0 - \frac{A}{(1+\epsilon_d)}\left[P_1^{(1+\varepsilon_d)} - P_0^{(1+\varepsilon_d)}\right].$$

Where the p_x is price, q_x is demand, and the subscript x reflects the subsidy (e.g. p_o) or hypothetical non-subsidy (e.g. p_1) conditions, respectively.

The second method simplifies this process by assuming unit elasticity across all groups and a linear demand curve, yielding a triangular-shaped DWL region:

$$DWL = \frac{(p_1 - p_o) \times \left(q_0 - (1 - f_p)q_0\right)}{2}.$$

Where f_p is the percentage increase in price and reflects the unit elasticity, and the product of $(1 - f_p)q_0$ is the estimated value of q_1. This is effectively calculating the area of a triangle bisecting a rectangle with height (p_1 - p_0) and length (q_o - q_1).

6.4.2.5.2.3 Social Cost of Carbon from Lighting Emissions

The social cost of carbon (SCC) represents the monetary value of damages that would arise from a metric ton increase of carbon dioxide. Alternatively, for existing emission sources, it can be interpreted as the benefit achieved by avoiding a metric ton of CO_2 emissions. In principle, the SSC is meant to capture the societal impacts of emissions, through its influence on climate change, on a wide range of factors that include market sectors, non-market sectors, energy production, resource availability and human health.

CO_2 is one of several climate-altering pollutants often considered in climate and energy-related policies that could be considered in the social cost of emissions. Reduction of short-lived climate forcers (SLCF) such as methane (CH_4) and black carbon (BC), are of particular interest to policymakers since reductions today would have benefits within decades. The climate impact of these pollutant species on Earth's energy system relative to CO_2 is often expressed by applying their respective global warming potentials (GWP). Once converted to their CO_2 equivalents (CO2-eq), the combined strength of a suite of pollutants can be summarized in a single value. While GWP values have been used in the past to derive social costs for non-CO_2 climate-altering species, caution is warranted. GWP values themselves are sensitive to the time horizon they are integrated over, which can shift their relative importance. Differences in the atmospheric lifetime and chemistry of non-CO_2 pollutants means that their social costs may not scale proportionally with

GWP. Furthermore, SCC estimates are based on globally mixed models and regional pollutants such as BC are known to exhibit differential impacts depending on where emissions occur. Recent studies have evaluated the potential uncertainty arising from applying CO_2-eq estimates to value the social cost of CH_4 and N_2O and suggest that CO_2-eq values generally underestimate the social cost of these species. For CH_4 and N_2O, these underestimates were as high as 24% and 36%, respectively, depending on their relative proportion to CO_2
(*27*).

6.4.3 Results

6.4.3.1 Kerosene End-Use

Table 6.4.3.1. Percent of households reporting use of kerosene for any lighting.

	Expenditure	**Electricity Supply**	**Households**	**Percent of Group**[1]
	2005 $/Person-day	*hrs/day*	*%*	*%*
Population			61.2 (0.4)	100
Electricity		No Electricity (Primary)	84.7 (0.6)	32.9 (0.6)
		< 16hrs (Secondary)	67.3 (0.6)	32.1 (0.5)
		> 16hrs (Secondary)	45.6 (0.6)	35.0 (0.6)
Urban	**< $2.00**	**All**	48.3 (0.7)	11.4 (0.2)
		< 16	63.8 (1.1)	5.0 (0.2)
		> 16	40.5 (0.9)	6.4 (0.2)
	> $2.00	**All**	24.8 (0.6)	6.9 (0.2)
		< 16	40.2 (1.3)	2.2 (0.1)
		> 16	21.0 (0.7)	4.7 (0.2)
		Urban Population	35.6 (0.5)	18.3 (0.3)
Rural	**< $1.25**	**All**	76.9 (0.6)	37.2 (0.6)
		No Electricity	83.5 (0.8)	20.1 (0.5)
		< 16	75.2 (1.3)	8.0 (0.3)
		> 16	66.5 (1.5)	9.1 (0.4)
	$1.25-2.00	**All**	73.5 (0.8)	24.9 (0.5)
		No Electricity	85.4 (1.4)	8.7 (0.3)
		< 16	72.5 (1.2)	8.3 (0.3)
		> 16	64.3 (1.7)	7.8 (0.4)
	>$2.00	**All**	66.3 (0.9)	19.7 (0.4)
		No Electricity	89.3 (1.4)	4.1 (0.3)
		< 16	70.2 (1.3)	8.5 (0.3)
		> 16	54.5 (1.3)	7.0 (0.3)
		Rural Population	73.1 (0.4)	81.7 (0.3)

[1] Group refers to: electricity service level status, urban/rural status, expenditure group level, electricity service level within expenditure group

6.4.3.2 Kerosene Consumption and Service

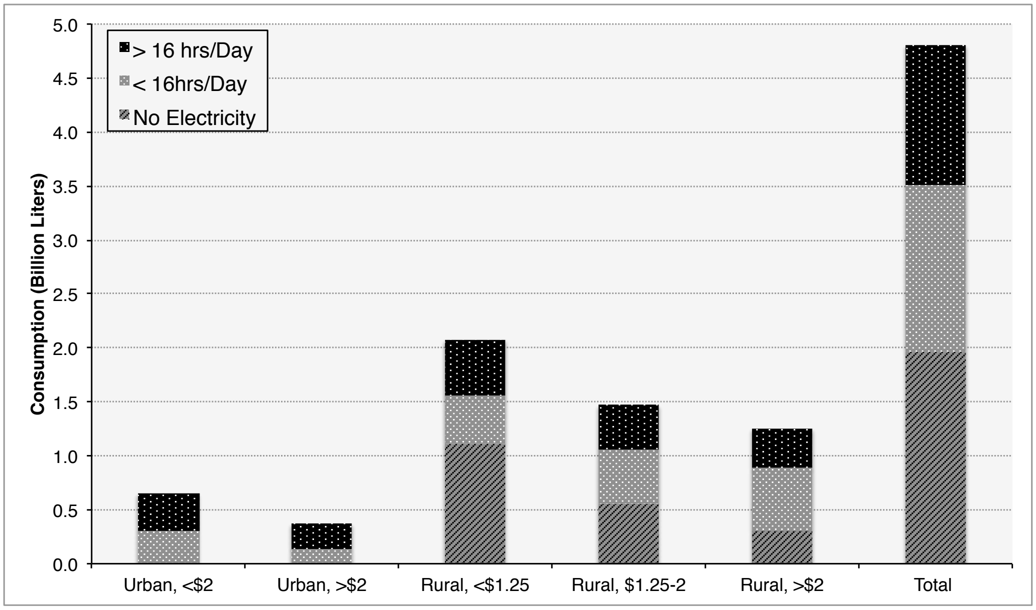


Figure 6.4.3.1. Kerosene lighting consumption estimates for 2005 by expenditure and electricity sub-populations.

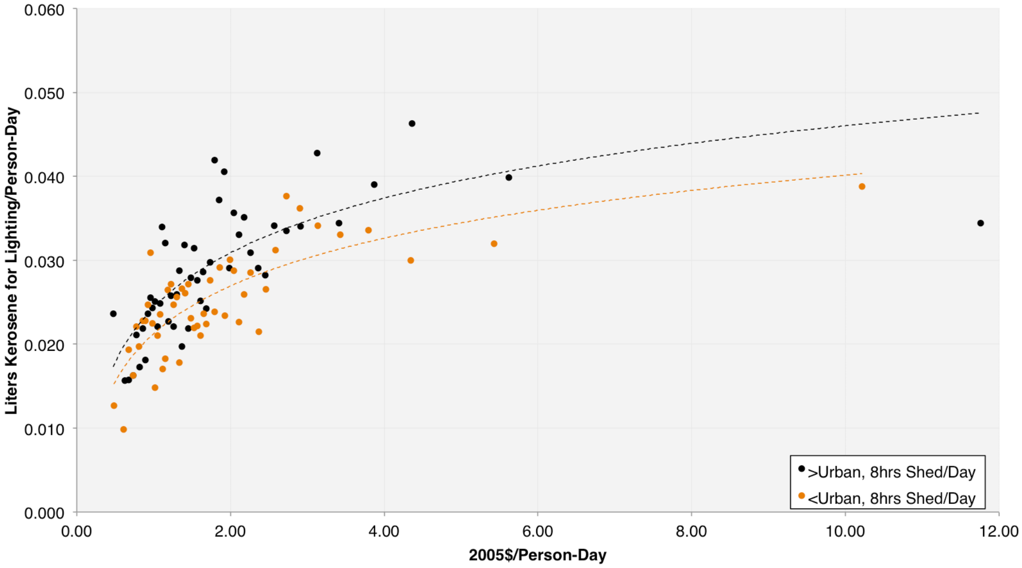


Figure 6.4.3.2. Urban kerosene consumption for lighting (liters/person-day) versus total household expenditure ($/person-day) among users. Values are compressed into 50 groups for visual clarity and dashed lines represent the line of best-fit. **< 16 hrs/day**: $y = 0.0094\ln(x)+0.0244$, $r\text{-}sq = 0.57$; **> 16 hrs/day**: $y = 0.0082\ln(x)+0.0212$, $r\text{-}sq = 0.62$.

Table 6.4.3.2. Average annual consumption of kerosene used for lighting across household group classifications among those reporting kerosene use for light (user households) and group-level (users and non-users).

	Expenditure Level	**Electricity Access Level**	**Kerosene Using**		**Full Group Population**	
	2005$/ Person-day	*Hours of Supply/day*	*Liters/ HH-Year*	*Liters/ Person-Year*	*Liters/ HH-Year*	*Liters/ Person-Year*
Population			43 (0.4)	9 (0.1)	26 (0.3)	6 (0.1)
Electricity Status		No Electricity	45 (0.5)	10 (0.1)	38 (0.5)	8 (0.1)
		< 16hrs (Secondary)	45(0.5)	9 (0.1)	30 (0.5)	6 (0.1)
		> 16hrs (Secondary)	40 (1.1)	9 (0.1)	18 (0.6)	4 (0.1)
Urban	**< $2.00**	**All**	**44 (0.6)**	**9 (0.1)**	**21 (0.4)**	**4 (0.1)**
		< 16	46 (0.8)	9 (0.2)	29 (0.7)	6 (0.2)
		> 16	42 (0.9)	8 (0.2)	17 (0.5)	3 (0.1)
	> $2.00	**All**	**41 (0.8)**	**10 (0.2)**	**10 (0.3)**	**2 (0.1)**
		< 16	47 (1.4)	11 (0.4)	19 (0.8)	4 (0.2)
		> 16	39 (1.0)	10 (0.3)	8 (0.3)	2 (0.1)
		Urban Population	**43 (0.5)**	**9 (0.1)**	**15 (0.3)**	**3 (0.1)**
Rural	**< $1.25**	**All**	**42 (1.0)**	**8 (0.2)**	**32 (0.9)**	**6 (0.1)**
		No Electricity	42 (0.6)	8 (0.1)	35 (0.6)	7 (0.1)
		< 16	42 (1.2)	7 (0.2)	31 (1.1)	5 (0.2)
		> 16	42 (3.9)	8 (0.6)	28 (3.0)	5 (0.5)
	$1.25-2.00	**All**	**44 (0.6)**	**10 (0.1)**	**32 (0.6)**	**7 (0.1)**
		No Electricity	47 (1.1)	11 (0.2)	40 (1.1)	10 (0.3)
		< 16	44 (1.0)	9 (0.2)	32 (0.9)	7 (0.2)
		> 16	39 (0.8)	9 (0.2)	25 (0.8)	6 (0.2)
	>$2.00	**All**	**46 (0.7)**	**12 (0.2)**	**31 (0.6)**	**8 (0.2)**
		No Electricity	53 (1.7)	15 (0.6)	47 (1.7)	13 (0.6)
		< 16	48 (1.1)	11 (0.3)	34 (1.0)	8 (0.3)
		> 16	39 (1.0)	10 (0.3)	21 (0.8)	6 (0.2)
		Rural Population	**43 (0.5)**	**9 (0.1)**	**32 (0.5)**	**7 (0.1)**

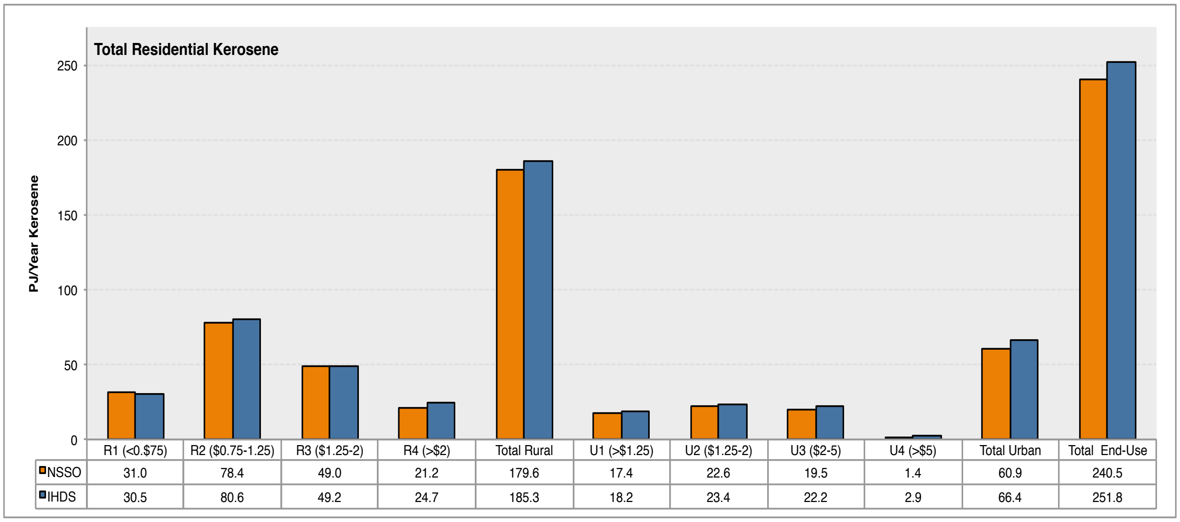
Table 6.4.3.3. Estimated service by reporting users and in an average household within the group classification (including non-users)

	Expenditure Level	Electricity Access Level	User Household Lighting Hours	User Household Lumen Hours	Average Household Lighting Hours	Average Household Lumen Hours
	2005$/ Person-day	*Hours of Supply/day*	*light-hrs/day*	*Lumen-hrs/Day*	*light-hrs/day*	*Lumen-hrs/Day*
Population			8.1 (0.1)	190 (2)	5.0 (0.1)	110 (1)
Electricity Status		No Electricity (Primary)	8.6 (0.1)	180 (2)	7.3 (0.1)	150 (2)
		< 16hrs (Secondary)	8.3 (0.1)	200 (3)	5.6 (0.1)	130 (2)
		> 16hrs (Secondary)	7.5 (0.2)	180 (4)	3.4 (0.1)	80 (2)
Urban	**< $2.00**	**All**	**8.8 (0.1)**	**160 (2)**	**4.2 (0.1)**	**80 (2)**
		< 16	9.2 (0.2)	170 (3)	5.9 (0.1)	110 (3)
		> 16	8.4 (0.2)	150 (3)	3.3 (0.1)	60 (2)
	> $2.00	**All**	**6.6 (0.1)**	**230 (2)**	**1.6 (0.0)**	**60 (2)**
		< 16	7.5 (0.2)	260 (8)	3.0 (0.1)	100 (5)
		> 16	6.2 (0.2)	220 (6)	1.2 (0.0)	40 (2)
		Urban Population	**8.0 (0.1)**	**190 (2)**	**2.8 (0.0)**	**70 (1)**
Rural	**< $1.25**	**All**	**8.5 (0.2)**	**150 (4)**	**6.5 (0.2)**	**120 (3)**
		No Electricity	8.5 (0.1)	150 (2)	7.1 (0.1)	130 (2)
		< 16	8.4 (0.3)	150 (5)	6.3 (0.2)	110 (4)
		> 16	8.4 (0.8)	150 (14)	5.6 (0.6)	100 (11)
	$1.25-2.00	**All**	**8.2 (0.1)**	**180 (2)**	**6.0 (0.1)**	**130 (2)**
		No Electricity	8.9 (0.2)	200 (5)	7.6 (0.2)	170 (5)
		< 16	8.2 (0.2)	180 (4)	6.0 (0.2)	130 (4)
		> 16	7.5 (0.2)	170 (3)	4.8 (0.2)	110 (3)
	>$2.00	**All**	**7.5 (0.1)**	**250 (4)**	**5.0 (0.1)**	**170 (3)**
		No Electricity	8.6 (0.3)	290 (10)	7.6 (0.3)	260 (9)
		< 16	7.9 (0.2)	270 (6)	5.5 (0.2)	190 (6)
		> 16	6.4 (0.2)	220 (6)	3.5 (0.1)	120 (4)
		Rural Population	**8.2 (0.1)**	**190 (2)**	**6.0 (0.1)**	**140 (2)**

6.4.3.2.1 Survey Comparison: IHDS and NSSO

As a check of kerosene consumption estimates derived from an analysis of IHDS 2005, results were compared to those from an analysis of the National Sample Survey Organization 61st Round metadata taken during 2004-5 (*28, 29*). Household consumption on kerosene was estimated across expenditure quartiles separately in urban and rural sectors and scaled using identical population proportions. There are several key differences in the way IHDS and NSSO measure residential energy use that have been discussed previously. Briefly, NSSO does not collect activity information for all fuels, but does measure a primary energy source for cooking and lighting (not heating). NSSO collects information on electricity connection but does not measure reliability.

Total consumption estimates using IHDS and NSSO surveys agreed reasonably well, with total demand between the two survey differing by less than 10-15%, and strong agreement across expenditure levels and urban/rural sectors (**Figure 6.4.3.3, Table 6.4.3.4**). Agreement was also consistent when evaluated separately by kerosene purchased through PDS and the open market (**Figure 6.4.3.4a-b**).

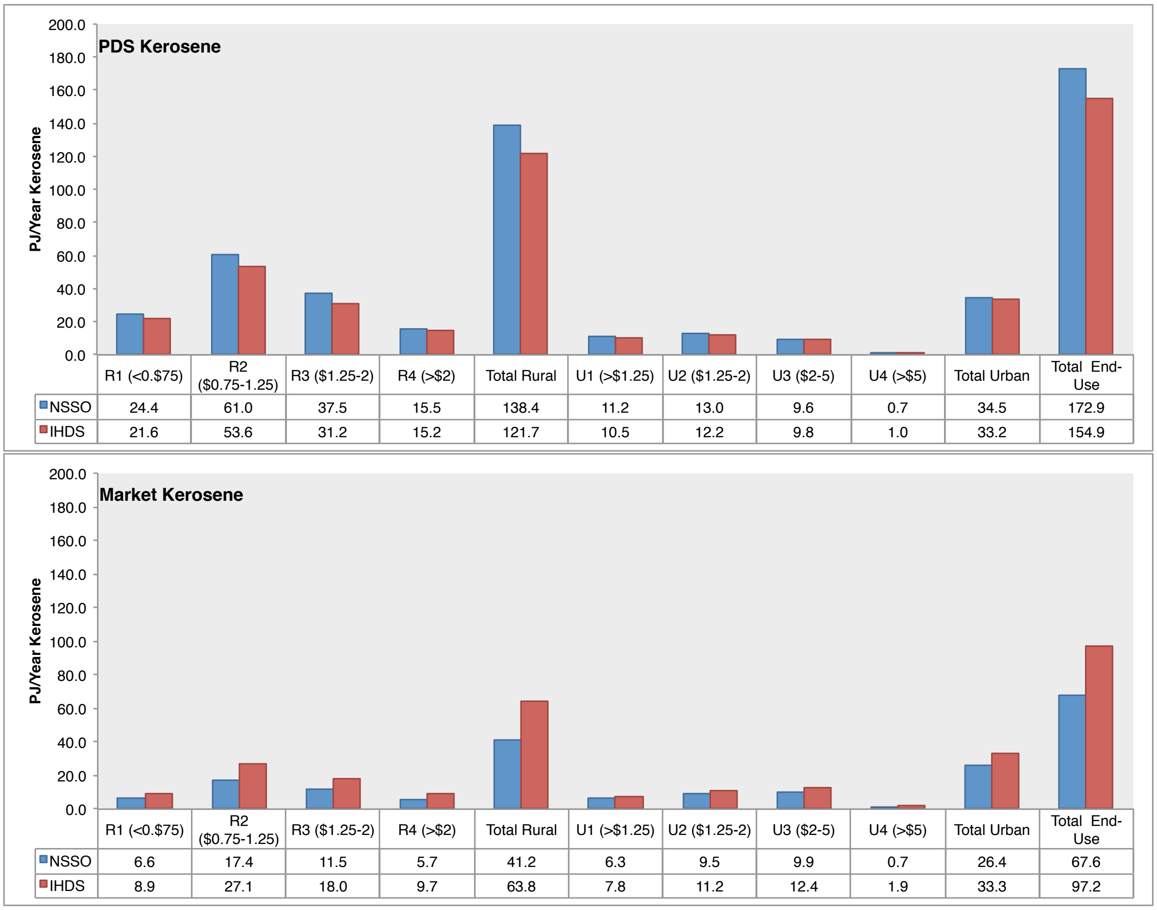


	R1 (<0.$75)	R2 ($0.75-1.25)	R3 ($1.25-2)	R4 (>$2)	Total Rural	U1 (>$1.25)	U2 ($1.25-2)	U3 ($2-5)	U4 (>$5)	Total Urban	Total End-Use
🟧NSSO	31.0	78.4	49.0	21.2	179.6	17.4	22.6	19.5	1.4	60.9	240.5
🟦IHDS	30.5	80.6	49.2	24.7	185.3	18.2	23.4	22.2	2.9	66.4	251.8

Figure 6.4.3.3. NSSO and IHDS estimated residential kerosene consumption (all activities) over expenditure groups

Table 6.4.3.4. Comparison of residential kerosene consumption (*PJ*) by activity and purchase source based on NSSO 61st Round (2005) data and IHDS (2005).

			Total Rural	**Total Urban**	**Total End-Use**
		$/Person-Day			
Activity	**Lighting**	NSSO	172.8	5.8	179
		IHDS	142.1	25.6	168
		*PJ Difference (%)**	*30.7 (22)*	*-19.8 (-77)*	*10.9 (7)*
	Cooking	NSSO	6.9	55.1	62.0
		IHDS	34.4	30.4	64.8
		*PJ Difference (%)**	*-27.5 (-80)*	*24.7 (81)*	*-2.9 (-4)*
	Heating	NSSO	*ND*	*ND*	ND
		IHDS	2.2	3.2	5.4
		*PJ Difference (%)**	---	---	---
Source	**PDS**	NSSO	138.4	34.5	172.9
		IHDS	121.7	33.2	154.9
		*PJ Difference (%)**	*16.7 (14)*	*1.2 (4)*	*18.0 (12)*
	Market	NSSO	41.2	26.4	67.6
		IHDS	63.8	33.3	97.2
		*PJ Difference (%)**	-22.6 (-35)	-6.9 (-21)	*-29.5 (-30)*
Total		**NSSO**	**179.6**	**60.9**	240.5
		IHDS	**185.3**	**66.4**	251.8
		*PJ Difference (%)**	***-5.7 (-3)***	***-5.6 (-8)***	*-11.3 (-4)*



	R1 (<0.$75)	R2 ($0.75-1.25)	R3 ($1.25-2)	R4 (>$2)	Total Rural	U1 (>$1.25)	U2 ($1.25-2)	U3 ($2-5)	U4 (>$5)	Total Urban	Total End-Use
🟦 NSSO	24.4	61.0	37.5	15.5	138.4	11.2	13.0	9.6	0.7	34.5	172.9
🟥 IHDS	21.6	53.6	31.2	15.2	121.7	10.5	12.2	9.8	1.0	33.2	154.9

	R1 (<0.$75)	R2 ($0.75-1.25)	R3 ($1.25-2)	R4 (>$2)	Total Rural	U1 (>$1.25)	U2 ($1.25-2)	U3 ($2-5)	U4 (>$5)	Total Urban	Total End-Use
🟦 NSSO	6.6	17.4	11.5	5.7	41.2	6.3	9.5	9.9	0.7	26.4	67.6
🟥 IHDS	8.9	27.1	18.0	9.7	63.8	7.8	11.2	12.4	1.9	33.3	97.2

Figure 6.4.3.4a-b. Residential kerosene consumption (PJ/year) of subsidized PDS (top) and open market (bottom) kerosene over urban and rural household expenditure groups.

6.4.3.2.2 Statistical Associations Between Consumption and Household Characteristics

A simple linear regression was used to summarize the association between lighting consumption and households characteristics. Reported volumetric consumption of kerosene for lighting among households using kerosene for light was regressed on household characteristics used to disaggregate households into analysis groups:

$$Y_i\left(\frac{Liters}{Month}\right) = \beta_1 EXPEND_i + \beta_2 NPERSON_i + \ \beta_3 URBAN_i + \ \beta_4 I.ACCESS_i + \epsilon_i$$

Where *EXPEND* is the monthly household expenditure (2005$), NPERSON is the number of household members, URBAN is an indicator for urban/rural, I.ACCESS is an indicator variable for the three electricity access levels (no electricity, <16 hrs-day of supply, >16hrs/day of supply) with no electricity as the reference group. **Table 6.4.3.5** presents coefficients and corresponding standard errors. Selected covariates explain a relatively low fraction of the variability (R-squared = 0.13), but are significant. Adding indicators for state and fuel prices, explains a slightly larger fraction of the variability (R-squared = 0.20).

Table 6.4.3.5. Coefficients and standard errors of a regression of annual household consumption of lighting kerosene (liters) on household characteristics.

Group Variable		Coefficient (SE)
Total Household Expenditure		0.013 (0.001)**
Household Size		2.95 (0.09)**
Urban		1.73 (0.48)**
Electricity Status		
	< 16 hrs/day	-3.50 (0.78)**
	> 16 hrs/day	-7.40 (0.78)**
Int.		26.9 (0.82)**

*** P < 0.01*

6.4.3.2.3 Reported Expenditure and Volumetric Monthly Consumption

IHDS measures both the household expenditure and volumetric purchase of kerosene over the previous 30-day period. Reported expenditure can be converted to volumetric units using household reported unit prices. In several analyses, kerosene volume was estimated by dividing the reported kerosene expenditure by the volume-weighted unit cost (*$/Liter*). As a sensitivity check, we estimate the Urban/Rural relationship using both reported and estimated consumption volumes. Results suggest a high agreement between methods, yielding expenditure coefficient estimates within 10%. **Figure 6.4.3.5** shows the rural relationship for illustration.

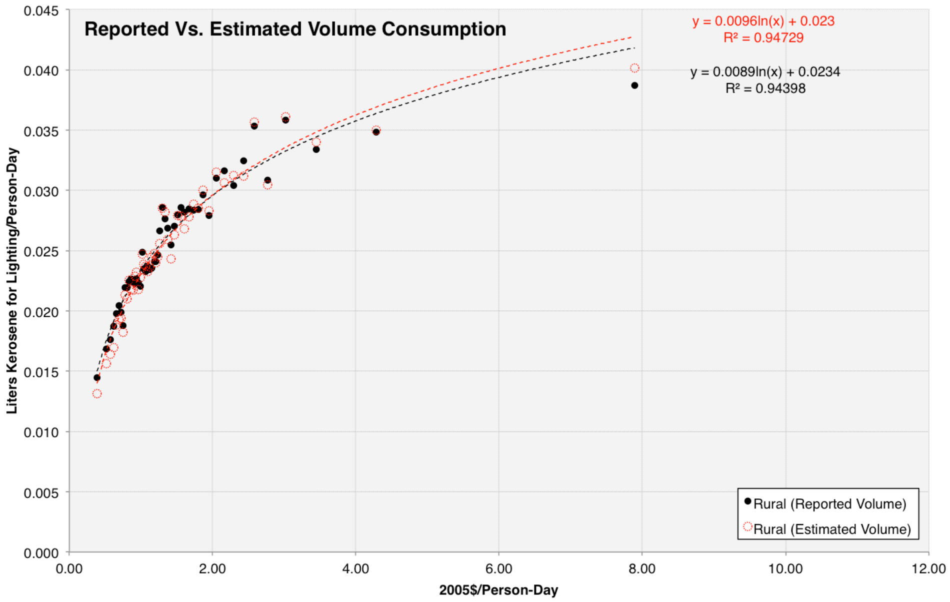


Figure 6.4.3.5. Comparison between fuel consumption based on expenditure and corresponding fuel prices and reported volumetric consumption.

6.4.3.3 Kerosene Expenditure

In general, expenditure trends are consistent with those observed for consumption, with kerosene lighting expenditure increasing with total expenditure. For example, between the lowest and highest household expenditure groups, kerosene expenditure for light increased by 55% (3.7 $/person-year) in rural and 30% (2.3 $/person-year) in urban sectors. **Table 6.4.3.6** presents descriptive statistics on expenditure for kerosene over household groups.

Expressing kerosene consumption for lighting relative to total expenditure is a more meaningful measure of the financial burden to the household. Trends across expenditure groups indicate a modest relative expenditure ranging from 1-2%, but generally decreasing as total household expenditures increase; the converse of absolute lighting expenditure. Thus, while absolute expenditure on lighting kerosene increases with total expenditure, it constitutes a lower financial burden. It is important to note, however, that we cannot account for other sources of light energy and expenditure, thus it is unclear whether expenditure on lighting utilities is also changing. As with consumption, there is indication that electricity access modifies this relationship, with relative expenditure decreasing as electricity access improves. The idea that lower electricity access results in greater reliance on kerosene is fairly intuitive. However, homes with less electricity also pay a greater unit fuel cost, resulting from subsidized kerosene needing to be supplemented with more expensive market kerosene. For example, moving from the no electricity group to the highest supply level in rural areas results in a significant reduction in unit price of between 12-20%, depending on the expenditure group.

Table 6.4.3.6. Average annual expenditure, percent of user households, average price per liter, and the percent of kerosene obtained from PDS sources among those reporting kerosene use for light (user households).

	Expenditure Level	Electricity Access Level	Kerosene Expenditure	Percent of Total Expenditure	Avg. Unit Price	Volume from PDS
	2005$/ Person-day	*Hours of Supply/day*	*2005$/Year*	*%*	*2005$/Liter*	*%*
User Population			**7.9 (0.1)**	**1.6 (0.02)**	**0.85 (0.00)**	**76.9 (0.4)**
Electricity Status		No Electricity (Primary)	8.7 (0.2)	2.0 (0.03)	0.89 (0.01)	75.3 (0.9)
		< 16hrs (Secondary)	8.1 (0.1)	1.4 (0.02)	0.85 (0.00)	75.8 (0.6)
		> 16hrs (Secondary)	7.0 (0.2)	1.3 (0.04)	0.79 (0.01)	79.6 (0.6)
Urban	**< $2.00**	**All**	**7.2 (0.1)**	**1.6 (0.03)**	**0.86 (0.01)**	**71.9 (0.8)**
		< 16	8.1 (0.2)	1.9 (0.04)	0.92 (0.01)	68.3 (1.2)
		> 16	6.5 (0.1)	1.4 (0.03)	0.82 (0.01)	74.9 (1.2)
	> $2.00	**All**	**9.5 (0.2)**	**0.9 (0.03)**	**0.92 (0.01)**	**62.9 (1.4)**
		< 16	11.0 (0.4)	1.0 (0.04)	0.95 (0.02)	61.3 (2.0)
		> 16	8.7 (0.3)	0.8 (0.03)	0.91 (0.02)	63.7 (1.8)
		Urban Population	**8.1 (0.1)**	**1.3 (0.02)**	**0.88 (0.01)**	**68.6 (0.7)**
Rural	**< $1.25**	**All**	**6.5 (0.2)**	**2.1 (0.04)**	**0.84 (0.00)**	**80.1 (0.7)**
		No Electricity	6.8 (0.1)	2.2 (0.04)	0.87 (0.01)	76.7 (1.1)
		< 16	5.9 (0.2)	1.8 (0.06)	0.82 (0.01)	82.4 (1.3)
		> 16	6.2 (0.6)	1.9 (0.13)	0.77 (0.01)	85.9 (1.4)
	$1.25-2.00	**All**	**8.2 (0.1)**	**1.5 (0.03)**	**0.85 (0.01)**	**78.3 (0.9)**
		No Electricity	10.2 (0.3)	1.9 (0.05)	0.92 (0.01)	73.7 (1.6)
		< 16	7.7 (0.2)	1.4 (0.04)	0.84 (0.01)	78.2 (1.3)
		> 16	6.5 (0.2)	1.2 (0.03)	0.76 (0.01)	83.4 (1.4)
	>$2.00	**All**	**10.1 (0.3)**	**0.9 (0.02)**	**0.83 (0.01)**	**76.3 (1.0)**
		No Electricity	14.6 (0.9)	1.4 (0.08)	0.94 (0.02)	71.8 (2.8)
		< 16	9.8 (0.4)	0.9 (0.03)	0.83 (0.01)	75.0 (1.3)
		> 16	7.8 (0.2)	0.7 (0.02)	0.77 (0.01)	80.8 (1.3)
		Rural Population	**7.9 (0.1)**	**1.6 (0.02)**	**0.84 (0.00)**	**78.6 (0.5)**

6.4.3.4 Impacts and Alternate Scenarios

6.4.3.4.1 Emissions and Impacts from Primary $PM_{2.5}$ (Outdoor)

Table 6.4.3.7. Estimated pollutant emissions (Gg) from kerosene-fueled lighting in India in 2005 and in 2020 and 2030 under alternate scenarios.

Scenario[1]	**2005-6**				**2020**				**2030**			
	$PM_{2.5}$	BC	OC	SO_2	$PM_{2.5}$	BC	OC	SO_2	$PM_{2.5}$	BC	OC	SO_2
Baseline	250	230	14	1.5	260	240	17	1.7	220	200	16	1.6
UC	250	230	14	1.5	240	230	16	1.6	180	170	13	1.3
UCS	250	230	14	1.5	190	180	12	1.3	80	80	6	0.6
SPO	250	230	14	1.5	20	20	2	0.2	10	10	1	0.1
LED	250	230	14	1.5	180	170	0	1.0	0	0	0	0.0
FS	250	230	14	1.5	420	390	27	2.8	370	340	26	2.6

[1] UC = universal connection to electricity by 2030, UCS = UC + improved supply, SPO = subsidy phase-out by 2030, Solar = full replacement with zero end-use emissions, FS = full subsidy

6.4.3.4.1.1 $PM_{2.5}$ Control Costs: Pico-Solar LED

Emission controls costs can be divided into investment (lamp), fixed operating (e.g. wicks, lamp shielding) and variable operating (e.g. fuel) costs components. From this, the annual cost per unit of activity level is calculated relative to the Baseline technology and related to a pollutant emission using an average emission factor (gPM/MJ).

$$Cost_{control}\left(\frac{USD}{kgPM_{2.5}}\right) = \frac{(Cost_{Base} - Cost_{Control})}{(MJ_{base} \cdot EF_{base} - MJ_{control} \cdot EF_{control})} = \frac{(Cost_{Base} - Cost_{Control})}{(PM_{base} - PM_{control})}$$

Control costs are sensitive to various assumptions affecting components of lighting cost parameters – such as investment cost, fuel expenditure and household discount rates. As an exploratory estimate, we apply conservative estimates (in favor of kerosene technology) assuming a lower bound of annual kerosene consumption (~20 \$/HH-year), upper bound lifetime of kerosene devices (8 years versus 5 years for pico-solar) and a higher default discount rate than is assumed for energy technologies (50%). Both hurricane and pico-solar devices are assumed to have annual operating costs equivalent to 10% of the investment cost; no operating costs are assumed for simple wick lamps. Finally, comparisons do not consider differences in the quality of service (e.g. lumens) being provided to the user and we not consider costs associated with implementation potentially against (e.g. distribution infrastructure) or in favor (e.g. economy of scale effects) of solar devices.

6.4.3.4.2 Economic Impacts: Deadweight Loss and Social Cost of Carbon

6.4.3.4.2.1 SCC of Kerosene Lighting

Impacts of the pollutants emitted from the subsidization of kerosene for residential lighting comprise one component of the social cost of the subsidy. These are the external costs from pricing below private cost and indicated by the shaded region above deadweight loss in **Figure 6.4.2.6** published in Davis (2014). We apply the SCC concept to value the SCC of emissions of the two principle pollutant species emitted from kerosene lighting – CO_2 and black carbon. Together these species constitute over 98% of all carbon emissions from kerosene light sources.

Assuming the SCC at \$32 per metric ton CO_2, with lower and upper discount rated estimates of \$11 and \$51, CO_2 emissions in 2005 are valued at \$70 million, \$25 million and \$110 million, respectively. As an exploratory estimate, we also value the SCC-eq of black carbon using a conservative 100-year GWP of 700 (*30*). More recent estimates have estimated the average GWP for BC at 900 (*31*). Using the same SCC values applied above, the associated cost of BC emissions from the subsidization of kerosene for lighting in 2005 is \$850 million, or \$290 million and \$ 1.3 billion assuming the lower and upper discount rated SCC estimates, respectively. Considering the central estimates of the SCC-eq for CO_2 and BC yields a social cost due only to climate impacts of roughly \$900 million, which is similar in magnitude to estimated DWL. It is important to note that social costs valued here are from climate impacts only and could be expanded to consider other externalities, such as the direct impact of outdoor air pollution on health.

6.4.4 References

1. Energy Resources Institute, International Institute for Sustainable Development, "Evaluation of the pilot project on direct transfer of kerosene subsidies in Kotkasim, Alwwar," *GSI Report* (The International Institute of Sustainable Development, Geneva, Switzerland, 2014).
2. S. Desai, R. V, NCAER. (Inter-university Consortium for Political and Social Research Ann Arbor, 2009).
3. O. R. Masera, B. D. Saatkamp, D. M. Kammen, From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development* **28**, 2083-2103 (2000).
4. I. H. Rehman, P. Malhotra, R. C. Pal, P. B. Singh, Availability of kerosene to rural households: a case study from India. *Energy Policy* **33**, 2165-2174 (2005).
5. N. D. Rao, Kerosene subsidies in India: When enery policy fails as social policy. *Energy for Sustainable Development* **16**, 35-43 (2012).
6. B. V. Shenoy, "Lessons learned from attempts to reform India's kerosene subsidy," (International Institute for Sustainable Development (IIST), Geneva, Switzerland, 2010).
7. Lighting Global, in *IEC/TS 62257-9-5*. (International Electrotechnical Commission, 2014).
8. GEA, *Global Energy Assessment - Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012).
9. S. Pachauri, J. B. Ruijven, Y. Nagai, K. Riahi, D. Vuuren, A. Brew-Hammond, N. Nakicenovic, Pathways to achieve universal household access to modern energy by 2030. *Environmental Research Letters* **8**, (2013).
10. IIASA, in http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=about. (Inernational Institute of Applied Systems Analysis Laxenburg, Austria, 2013).
11. K. Riahi, F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, D. McCollum, S. Pachauri, S. Rao *et al.*, in *Global Energy Assessment - Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012), pp. 1203-1306.
12. S. Pachauri, A. Brew-Hammond, D. F. Barnes, D. H. Bouille, S. Gitonga, V. Modi, G. Prasad, A. Rath, H. Zerriffi, in *Global Energy Assessment - Toward a Sustainable Future*. (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012), pp. 1401-1458.
13. J. Apple, R. Vicente, A. Yarberry, N. Lohse, E. Mills, A. Jacobson, D. Poppendieck, Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air* **20**, 399-411 (2010).
14. E. Mills, The specter of fuel-based lighting. *Science* **308**, 1263-1264 (2005).
15. UNEP En.lighten. (United Nations Environment Program, 2014).
16. N. L. Lam, Y. Chen, C. Weyant, C. Venkataraman, P. Sadavarte, M. A. Johnson, K. R. Smith, B. T. Brem, J. Arineitwe, J. E. Ellis *et al.*, Household Light Makes

Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps. *Environmental Science & Technology* **46**, 13531-13538 (2012).

17. P. Alstone, P. Lai, E. Mills, A. Jacobson, High life cycle efficiency explains energy payback for improved off-grid lighting systems. *Journal of Industrial Ecology* **In Press**, (2014).
18. S. Mahapatra, H. N. Chanakya, S. Dasappa, Evaluation of various energy devices for domestic lighting in India: Technology, economics and CO2 emissions. *Energy for Sustainable Development* **13**, 271-279 (2009).
19. O. R. Messner, M. Strubegger, "User's guide for message iii," (International Institute of Applied Systems Analysis, 1995).
20. T. Ekholm, V. Krey, S. Pachauri, K. Riahi, Determinants of household energy consumption in India. *Energy Policy* **38**, 5696-5707 (2010).
21. Y. Nagai, Technical University of Vienna, Vienna (2014).
22. C. A. Pope, R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, G. Thurston, Lung cancer, cardiopulminary mortality and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association* **287**, 1132-1141 (2002).
23. C. A. Pope, M. Ezzati, D. W. Dockery, Fine particulate air pollution and life expectancy in the United States *The New England Journal of Medicine* **360**, 376-386 (2009).
24. M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj *et al.*, Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software* **26**, 1489-1501 (2011).
25. J. W. Vaupel, A. I. Yashin, "Targeting lifesaving: Demographic linkages between population structure and life expectancy," (International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria, 1985).
26. L. W. Davis, Welfare consequences of fossil fuel subsidies. *American Economic Review: Papers and Proceedings* **104**, 581-585 (2014).
27. A. L. Marten, S. C. Newbold, "Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide," *Working Paper #11-01* (US Environmental Protection Agency, Washington DC, 2011).
28. NSSO, "Household consumption of various goods and services in India, NSS 61st Round (July 2004 - June 2005), Report No. 509 (61/1.0/2)," (National Sample Survey Organisation, New Dehli, 2007).
29. NSSO, "Energy sources of India household for cooking and lighting, NSS 61st Round (July 2004 - June 2005), Report No. 511 (61/1.0/4)," (National Sample Survey Organisation New Dehli, 2007).
30. T. C. Bond, C. Zarzycki, M. G. Flanner, D. M. Kock, Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse. *Atmos. Chem. Phys.* **11**, 1505-1525 (2011).
31. T. Bond, Bounding the role of black carbon in the climate system: a scientific assessmnet. *American Geophysical Union*, (2013).