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Identifying and reducing the health and safety impacts of fuel-based lighting

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ABSTRACT

The inequity of costly and low-quality fuel-based lighting is compounded by adverse health and safety risks including burns, indoor air pollution, poisoning due to accidental ingestion of kerosene fuel by children, compromised visual health, maternal health issues, and reduced service in health facilities illuminated solely or sporadically with fuel-based lighting. This article compiles and synthesizes information on the health and safety impacts of fuel-based lighting from 135 reports spanning 33 countries. Energy efficient, off-grid lighting solutions offer the most promising and scalable means to eliminate adverse health outcomes, while lowering lighting costs and reducing greenhouse-gas emissions. Deployments seeking the greatest possible health benefit should target the most impacted geographical and demographic user groups. Because women and children are disproportionately impacted, improved lighting technologies for use by these groups will yield particularly significant health benefits.

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Context

Approximately 1.3 billion people throughout the developing world (one-fifth of humanity), lack access to electricity and rely instead on fuel-based lighting (IEA, 2014).[1] Uncounted businesses also find themselves in the same situation, and additional users on the electric grid face routine outages or energy costs forcing reversion to fuel-based light sources. Today, more people than the world's population at the time Edison introduced electricity spend nearly USD 40 billion annually (100 times the cost of an equal amount of electric light) to operate highly inefficient lamps (Mills, 2005). Lighting fuels are burned largely indoors and in close proximity to people, raising the question of more direct health and safety risks. Fuel-based lighting also contributes to climate change—itself a health and safety risk and compounder of poverty—by releasing substantial amounts of greenhouse-gas emissions (Mills, 2005) and black carbon (Lam et al., 2012a).

Many fuels are used to generate light, including kerosene,[2] propane, diesel, candles and a variety of biofuels. Quantifying health impacts is of critical importance. Adverse health effects are recognized (Baker and Alstone, 2011) but specific data and statistical indicators are rarely used in making the business case for alternatives. Improved information on current risks and potential health benefits of alternatives could also help identify and prioritize policy and market-based initiatives to replace fuel-based lighting with grid- and grid-independent alternatives powered by electricity.

The toxicity of lighting fuels has long been established within the medical literature (Pattle and Cullumbine, 1956). For example, direct exposure of kerosene is reported to have a wide range of consequences, including chemical pneumonia from ingestion, drying of skin and dermatitis from skin contact, symptoms consistent with CNS depression (e.g. headache, vertigo) from inhalation, neuralgia, memory loss, and effects on blood, kidney, and respiratory function (Gad and Pham, 2014). Kerosene contains known carcinogens such as benzene (American Cancer Society, 2006) and probable ones such as formaldehyde (US EPA, 2012), but studies have not focused on the cancer risks associated with indoor concentrations resulting from combustion in lanterns. Complicating such assessments, the composition of kerosene varies by refiner.

Kerosene is the most common fuel used for lighting in most countries (UNEP, 2013), although candles are dominant in some areas. The use of kerosene for lighting is far more common than as a "clean" primary fuel for cooking, and combustion in stoves is far more complete, producing fewer particulate emissions per unit of fuel burned than when burned in lanterns. Kerosene is a primary cooking fuel among only 4% of urban populations and 25% of rural populations in less-developed countries (Legros et al., 2009).

Scope and review methods

Documentation of off-grid lighting risks is far more extensive than typically cited in the energy and development literature, yet less extensive and academically rigorous than that of other energy-related risks such as those from cooking with solid fuels. Assembling a comprehensive

[1] This article was also published in report form by UNEP (Mills, 2014a).
[2] Common synonyms for kerosene include paraffin, no. 1 oil, coal oil, and lamp oil.

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picture of the existing knowledge requires assessing a broader range of sources than found in peer-reviewed scientific literature, including news reports, informal reports, and other documents.

This body of literature paints a detailed picture of multiple risks, including: unhealthful indoor air quality, injuries, poisonings, and compromised visual health. Moreover, the low quality of fuel-based illumination has negative impacts on the delivery of healthcare in poorly lit facilities. Violence against women is also inversely correlated with light availability. Few prior efforts (Mills, 2012; Lam et al., 2012b) have been made to synthesize or conduct a meta-analysis of the literature and reported data. This article provides the broadest review to date, comprising 135 reports of health issues related to off-grid lighting spanning 33 countries (Table 1). Underpinning the summary provided in this report, a database with additional detail has been posted online.[3]

While the source material varies widely, the base of evidence for lighting-related health impacts is firmly rooted in the peer-reviewed literature. Peer-reviewed studies include field reports (e.g., burns and accidental kerosene ingestion) as well as lab-based studies (e.g., pertaining to indoor air pollution from fuel-based lighting). The majority of relevant peer-reviewed studies are authored by medical professionals studying outcomes for patients in individual hospitals. While hospital reports provide a measure of risk prevalence, they capture only a small subset of impacts, especially in developing countries where hospitals are often inaccessible or injuries otherwise go unreported. Also, hospital records can attribute lighting to acute impacts, such as injuries (e.g., burns, poisonings), but not to disease from chronic exposures (e.g., poor indoor air quality). Some topics, such as house fires, are described primarily in gray-literature studies by local NGOs or news reports.

Synthesis of current understanding

The literature synthesized in this article provides a high-level, global picture of morbidity and mortality risks associated with fuel-based lighting:

- Fuel-based lighting is a significant cause of severe burn injuries, with particularly high death rates (24% of those admitted to hospitals, on average) in cases where kerosene is adulterated with other fuels and results in explosions, and a 6% mortality rate in other cases. Where destructive house fires are involved, decimating the hard-earned wealth of uninsured poor people, the resulting poverty and deprivation from being homeless can lead to additional harms.
- Indoor pollutants from fuel-based lamps include concentrations of particularly unhealthful PM2.5 particles an order of magnitude higher than health guidelines. Correlations with cataract and tuberculosis have been observed, but require further study to confirm and quantify causal links to off-grid lighting. Risks from fuels other than kerosene have not been studied.
- Unintentional ingestion of kerosene is the leading cause of child poisoning in the developing world. It is typically the number-one cause of child poisoning in developing countries, with an average mortality rate of 7% for the studies reviewed.
- Illumination levels from fuel-based lanterns are only 1% to 10% of those recommended by lighting authorities in industrialized countries. Users complain of vision-related problems and eye irritation, but formal measures of health and welfare impacts are limited. Inadequate illumination in clinics creates visual performance challenges that impede the delivery of quality healthcare, and discourages patients from seeking care. Some reports detail the risks of adverse outcomes in clinics such as maternal and infant mortality as well as difficulties maintaining good sanitation, which can lead to increased incidence of infections.
- Existing data suggest that fuel-based lighting injuries and pollutant exposures disproportionately affect women and children.
- Replacing intrinsically dangerous fuel-based lighting with electric light sources is the most promising and scalable way to reliably eliminate these risks.

There are few large-scale or statistically representative assessments of health impacts associated with off-grid lighting. As described below, many studies report that accidental ingestion of kerosene is the primary case of child poisoning in the developing world. In South Africa, 79,750 very young children are estimated to unintentionally ingest kerosene each year (160 per 100,000; occurring in 3.6% of all households) of which 60% develop a chemically induced pneumonia (Paraffin Safety Association, 2004). Also in South Africa, over 200,000 people are estimated to be injured or lose property each year due to kerosene-related fires, or 400 per 100,000 (Paraffin Safety Association, 2012a). Kimemia et al. (2014) estimate that 40%, or 400 to 700 of all settlement fires in South Africa are attributed to candles, and 14% of burn injuries. In Bangladesh, kerosene lamps are responsible for 23% of infant burns (Mashreky et al., 2008), corresponding to about 17,000 annual injuries nationally. Three multi-year reviews of admissions to Nigerian hospitals attributed approximately 30% of all burn cases to kerosene lamp explosions (Asuquo et al., 2008; Oludiran et al., 2009; Olaitan et al., 2007). Even higher burn rates (approximately 40% of all burns) are attributed to kerosene lamps in Sri Lankan homes, with 150 to 200 lives lost annually, with a cost for associated medical care of USD 1M annually (Shepherd and Perez, 2007).

A complex array of social, political, and behavioral factors contribute to the problem, including lack of product safety labeling or warnings, illiteracy (inability to receive communications about risk), overcrowding (contributes to rapid spread of fires and peoples' proximity to lantern emissions), corruption and fuel subsidies (resulting in fuel adulteration; Mills, forthcoming-b), unsupervised children, poverty (inability to afford child-safe containers for fuels), cultural practices such as keeping lamps next to young children while they sleep, to ward off “evil spirits” (Mashreky et al., 2008), ineffective or counterproductive folk remedies (for example, inducing vomiting after kerosene ingestion which causes undesirable aspiration of kerosene into the lungs) (Azizi et al., 1994), and, unwillingness or inability to seek professional care following injuries.

Self-reported risks and symptoms

Users of fuel-based lighting exhibit widely varying awareness of the risks. For example, a statistically representative survey of 3300 fuel-based lighting users across five sub-Saharan African countries found 26% to express related health concerns (Baker and Alstone, 2011). Within this group, perceived risk of fuel-based lighting on health varied widely: 57% in Zambia, 44% in Kenya, 21% in Tanzania, 14% in Ghana, and 4% in Ethiopia. Fig. 1 summarizes the users' specific concerns.

In another proxy of user awareness, a study in the Philippines found that only 9% of users cited perceived safety and health benefits as a reason for seeking alternatives to fuel-based lighting (Planete d'Entrepreneurs, 2011). The only demographic factor reported to correlate with reduced injury is income, with wealthier individuals using safer practices (Schwebel et al., 2009a).

The following sections provide further details, organized by type of health and safety risk.

Burns

There is no global estimate of burn-injuries attributable to fuel-based lighting. However, more than 95% of deaths worldwide from all types of burns occur in the low- and middle-income countries (WHO,

[3] Online database of health-related impacts from kerosene lighting (https://docs.google.com/a/lbl.gov/spreadsheet/ccc?key=0Avq_VXuy99CEdFVMaHJySWVsNnVvZkF2Nm4tN2pqMXc#gid=0).

Table 1
Summary of reports on health and safety incidents related to fuel-based lighting.

Type of incident or impact	Number of reports	Number of countries	Countries	Type of source
Structure fires	23	11	Bangladesh, China, India, Liberia, Namibia, Nepal, Philippines, Senegal, South Africa, Tanzania, Uganda	Largely news reports, with some NGO publications and databases
Kerosene burns	24	10	Bangladesh, India, Mozambique, Nepal, Nigeria, Philippines, South Africa, Sri Lanka, Uganda, Zimbabwe	Largely peer-reviewed articles from the medical literature
Kerosene explosions	23	6	India, Niger, Nigeria, Papua New Guinea, Sierra Leone, South Africa	Predominantly peer-reviewed literature, with some government studies and news reports
Kerosene ingestion	35	20	Antigua and Barbuda, Barbados, China, Ghana, India, Iraq, Israel, Jamaica, Jordan, Kenya, Libya, Malawi, Malaysia, Nepal, Nigeria, Pakistan, Sierra Leone, South Africa, Sri Lanka, Zimbabwe	Largely peer-reviewed articles from the medical literature, as well as NGO surveys
Indoor air quality (laboratory and field studies)	16	4	Ghana, Malawi, Nepal, Philippines	Largely peer-reviewed literature
Visual performance or health	8	7	Ethiopia, Ghana, Kenya, Nepal, Tanzania, Thailand, Zambia	Peer-reviewed literature, academic reports, NGO reports
Women's health	6	5	India, Nigeria, Sierra Leone, Tanzania, Zambia	Peer-reviewed literature and NGO reports
Total	135	33		

2002a). The mortality rate is five times higher in low- and middle-income populations in Africa than in high-income countries in Europe (World Health Organization, 2002a). In South-East Asia, the rate is 8.3-times greater than in Europe. The World Health Organization estimated that global deaths from burns and smoke inhalation during structural fires were on the order of 322,000 in the year 2002, which Peck et al. (2008) refer to as likely a "gross underestimate." In an even lower estimate, the number of burns was placed at 195,000 for the year 2008 (World Health Organization, 2012b).

Burns are a leading cause of injury among children, and fuel-based lighting is the primary cause among young children.[4] In southern India, burns are the number-two cause of injury-related mortalities among children, just over half of which are due to lanterns (9.3% of total injury-related mortalities) (Kanchan et al., 2009). A survey of 134 households in the Philippines found that 18% had experienced burns due to kerosene (presumably lighting plus cooking) (Planete d'Entrepreneurs, 2011). Mashreky et al. (2008) found that burns caused by fuel-based lighting occur disproportionately more often for infants than do other causes of burns (Fig. 2).

Lighting-related burns can result from structural fires, direct contact with hot lamps or flames, and explosions due to the adulteration of kerosene with other fuels. While there is a wide range of fuel-based lantern types, the literature does not generally identify the type involved. Open-flame devices (kerosene wick lamps or candles) pose the greatest risk.

Burn injuries are often followed by infection, and subsequently by disability and psychosocial trauma. Lighting-related burn injuries are pervasive in the developing world, with incidents documented in Bangladesh, China, India, Liberia, Mozambique, Namibia, Nepal, Niger, Nigeria, Papua New Guinea, the Philippines, Senegal, Sierra Leone, South Africa, Sri Lanka, Tanzania, Uganda, and Zimbabwe.

The publications reviewed here reflect a 6% weighted-average death rate from regular burns and 24% in the case of lantern explosions. It is important to reiterate that the literature is based primarily on studies of individuals admitted to hospitals, and thus reflects only a small subset of all cases that occur in the broader population. These cases tend to be particularly severe. For example, of the 1368 cases studied by Jayarama et al. (1993) one-third were fatal.

Statistics for burns caused by lighting fuels other than kerosene are rare. The Paraffin Safety Association (2012a,b), collected extensive data on injuries associated with lighting by candles. They find that candles—three-times more common than kerosene for lighting in South Africa (Statistics South Africa, 2012)—are implicated in one-third of burn injuries in the country, with 58% of the injuries involving males. Females are in the majority for the 0- to 24-year age groups. Elsewhere in sub-Saharan Africa, candles are used as a source of light in non-electrified households by 79% in Zambia, 20% in Ethiopia, 19% in Tanzania, 18% in Ghana, and 10% in Kenya (Baker and Alstone, 2011).

Structure fires

Over a century ago, large fires in China, displacing 1000 families in one case, were traced to kerosene lamps imported from the United States of America. This problem was relayed by the U.S. President to Congress as a matter affecting foreign relations with China (United States Department of State, 1889). Many subsequent fires in residences in the developing world were caused by fuel-based lighting. When fires occur in informal settlements, slums or camps for displaced persons, they spread rapidly due to crowding and flammability of housing materials. Newspaper accounts report some very large fires, such as one affecting 3000 people in a Philippine informal settlement in 2009, killing 16 (Daily Mail, 2009).[5] The former fire chief in Monrovia, Liberia notes the occurrence of an average of one candle-related "shack fire" every week (Dawson, 2013).

Nearly 24,000 fires in informal housing settlements were recorded nationally in South Africa between 1998 and 2006, resulting in 1088 deaths (Birkenshaw, 2008). Swart (2012) estimates that 30% of shack fires in the country are started by candles. Kimemia et al. (2014) put the value at 40% of fires and 15% of burn injuries. A random sample of households in South Africa found that kerosene-related fires (presumably for cooking as well as lighting equipment) had occurred in 6.3% of all households (Matzopoulos et al., 2006).[6]

Explosions resulting from the adulteration of kerosene with other fuels

The adulteration of kerosene with gasoline or diesel fuel creates a volatile mix that can ignite and explode.[7] The resulting injuries are severe, and often fatal. Some unscrupulous oil merchants adulterate kerosene with other fuels when they are even slightly less expensive, or during times of kerosene scarcity (Babalola and Ekiti, 2011). Unintentional adulteration can also occur when end-users utilize the same containers for gasoline and kerosene or suppliers inadequately isolate or flush mixed-use pipelines or tanks. Given that individuals often purchase kerosene

[4] See http://www.healthmetricsandevaluation.org/gbd/visualizations/gbd-cause-patterns.

[5] Other examples include fires destroying 200 homes in India in 2010 (Thaindian News, 2010), and 1500 homes – killing 15 – in Bangladesh in March 2000 (Associated Press, 2000). Refugee camps are also vulnerable, as in the case of a Nepali camp where 1200 of 1500 homes were burned by a fire suspected to have been started by a lantern, leaving 12,000 homeless (UCRI, 2010). Slum fires are a routine occurrence.

[6] One fire there, attributed to a single candle, killed two people while destroying 500 homes and leaving 2000 people homeless (The Mercury, 2010).

[7] The lowest temperature at which kerosene vaporizes and forms an ignitable mixture in air is at least 38 °C, which drops to about 5 °C with only 10% adulteration with gasoline (Shepherd and Perez, 2007). Explosions occur most easily when lanterns are refueled while lit, and the evaporating fumes ignite.

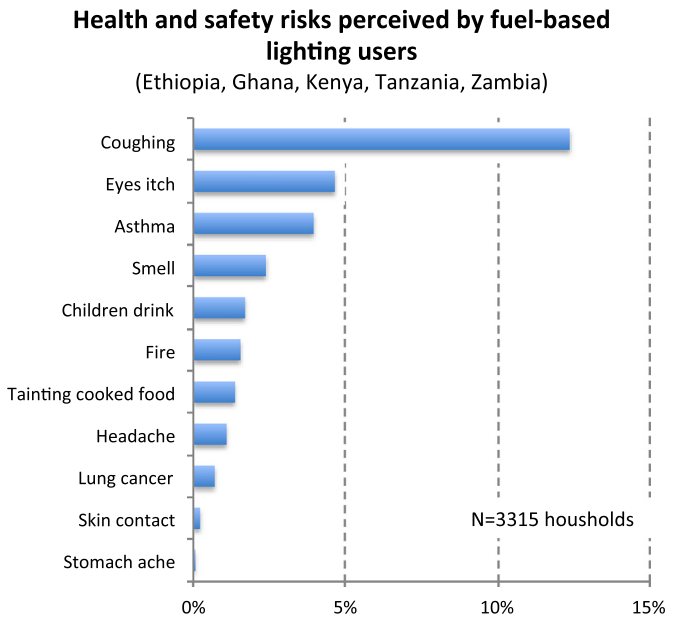

Fig. 1. Perceived health consequences of fuel-based lighting and inadequate service levels. Source: Baker and Alstone (2011).

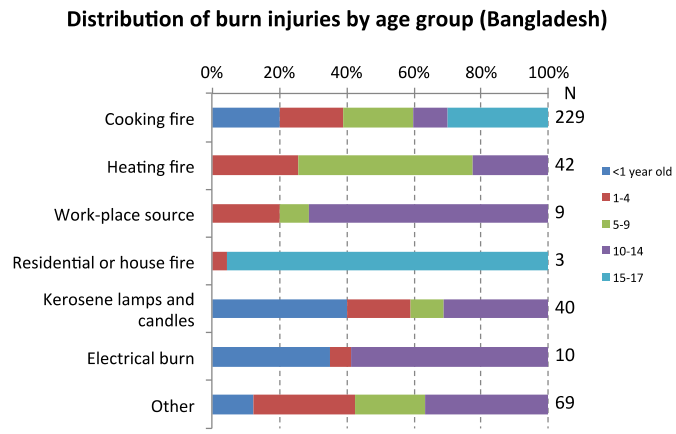

Fig. 2. Infants incur about 40% of the burns caused by fuel-based lighting in Bangladesh, the leading causal factor for that age group in that country. (For interpretation of the reference to color in this figure legend, the reader is referred to the web version of this article.)
Adapted from Mashreky et al. (2008).

in small quantities, modest amounts of adulterated kerosene can be disseminated to large populations.

Reports of kerosene adulteration have emerged from India, Niger, Nigeria, Papua New Guinea, Sierra Leone and South Africa. Reports are most common in Nigeria (Lawal, 2011). A report of kerosene adulteration that impacted 2500 people, of which 368 (14%) died, came from Nigeria's Edo region (Bernard, 2011). In one household, 8 of 10 family members were killed (Ugburo et al., 2003). These incidents are frequent; long-term studies find chronically high rates of hospital admissions due to explosions in Nigeria. One event in India (Gupta et al., 1996) affected 303 people. With only 10 beds available in the local hospital's emergency burn unit, many patients were turned away or referred to distant hospitals. In two cases from India, 48,000 and 72,000 l of fuel were adulterated in the same month (The Telegraph, 2011a,b).

Three multi-year reviews at Nigerian hospitals attributed around 30% of all burn cases to kerosene fuel explosions (stoves plus lanterns) (Dongo et al., 2007; Asuquo et al., 2008; Olaitan et al., 2007). In the latter study, injuries to females outnumbered those to men by nearly 3:1. In another study (covering just one month), 96% of burn admissions were due to kerosene device explosions. Of those burned, 62% were children and 60% were female; the average body-area burned was 24% (with a 44% overall mortality rate) (Oduwole et al., 2003). The month covered by the study followed the discovery that a petroleum storage depot deliberately adulterated the kerosene before sale. Oludiran et al. (2009) found that 52% of children (half below the age of 3) admitted to a hospital for burns received their injuries from exploding kerosene lanterns or stoves, with burns covering between 6% and 50% of body area. Oduwole et al. (1988) observed 100% mortality for cases with burns covering more than 18% of total body area. Another author found that half the admissions were children, with a nearly 6-fold increased admission rates at one hospital following an incident in 1984, with 47% mortalities versus none for burns in the same month, prior year (Grange et al., 1988).

Indoor air pollution

Poor indoor air quality in developing countries creates a large societal burden, both economic and humanitarian (Zhang and Smith, 2007). Fuel-based lanterns are located in close proximity to users; they emit small-diameter particles that can be inhaled deeply into the lungs. Other emissions resulting from burning kerosene include carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen dioxide, formaldehyde, and various volatile organic carbons (VOCs). As of 2010, an estimated 2.6 to 4.4 million deaths (Lim et al., 2013) occur each year from poor indoor air quality associated with cooking with solid fuels in the developing world. These deaths are sometimes incorrectly attributed to lighting; no such estimate has been in fact been made and the risks are substantially lower (Lam, 2013).

Inhalation of particulates resulting from indoor combustion can cause a range of adverse health effects (Bai et al., 2007; Pokhrel et al., 2010; Lam et al., 2012b). Among the potentially harmful effects are impairment of ventilatory function (Behera et al., 1991) and a higher incidence of acute lower respiratory infection among those using kerosene and biofuels (Sharma et al., 1998). One of the potential consequences of indoor pollutants from kerosene lanterns is tuberculosis, a major health issue in the developing world. In the only study to explore the role of lighting, researchers found the odds of having tuberculosis in Nepal were more than nine-times greater for women using kerosene lamps for indoor lighting than those using electric light (Pokhrel et al., 2010). The authors did not have detailed measures of lighting behaviors that may have contributed to this risk but note that kerosene lamps may burn less efficiently, for longer hours, and release emissions closer to users than do stoves.

VanVliet et al. (2013) offers one of the only studies to measure lighting-related particulates in actual occupied homes, and found a significant contribution from kerosene lanterns above that traced to biofuels used for cooking. Measurements by Apple et al. (2010) demonstrated that night vendors who use a single simple wick lamp in simulated high-air-exchange market kiosks will likely be exposed to dangerous PM2.5 concentrations that are an order of magnitude greater than ambient health guidelines (WHO, 2006). Thanks to more efficient combustion, using a hurricane lamp will reduce exposure to PM2.5 and PM10 concentrations by an order of magnitude compared to a simple wick lamp. There are no known standards regulating emissions of or exposure to particulates produced from fuel-based lanterns. It should be noted that the particulate emissions of kerosene lanterns (and likely candles; Zai et al., 2006) also represent significant amounts of black carbon, strongly implicated in climate change (Lam et al., 2012a). Estimates of ultimate indoor exposure to total PM emissions found that those of kerosene lamps were approximately three times that of candles (Fan and Zhang, 2001).

Studies to date on the indoor air quality impacts associated with lighting fuels have focused on kerosene. Little assessment has been made of health issues associated with lighting-related uses of certain other fuels, including candles, diesel, animal and vegetable oils, dung, or fuel wood. Fine et al. (1999) identified approximately 150 organic compounds present in candle smoke and unburned candle wax. Concerns in addition to fuel-

combustion products are wicks made with lead cores as a stiffening agent[8] and lantern mantles made with radioactive thorium, neither of which are accompanied with safety warnings or disposal instructions when sold in the developing world. Burning candle wicks have been shown to yield indoor concentrations of lead above ambient air standards and workplace standards (Wasson et al., 2002).

While indoor particulate matter concentrations from cook stoves have been extensively studied, characterization of particulate concentrations from fuel-based lighting has received minimal attention (Schare and Smith, 1995; Fan and Zhang, 2001; Apple et al., 2010; VanVliet et al., 2013). This is unfortunate, given that fuel-based lighting and dirty cooking fuels often exist in the same households and the relative effects need to be isolated. Lighting combustion is generally poorer than that in liquid-fuelled stoves; the mix of particle types and sizes will vary by fuel and even lantern type. According to an estimate by Poppendieck et al., human inhalation of particulate matter from simple wick lamps is about 5-times less than that of cook stoves, yet is also about 5-times more than from ambient air (2010).[9] Lam (2013) found the gap between lighting and cooking to be smaller than this. Fullerton et al. (2009) found higher levels of particulate matter associated with macrophage cells in people living with kerosene lamps, particularly simple wick-based lamps but also with hurricane lanterns and candles, which have particularly incomplete combustion.

Unintentional poisoning

Unintentional poisoning resulting from the drinking of kerosene has been reported in Antigua and Barbuda, Barbados, China, Ghana, India, Iraq, Israel, Jamaica, Jordan, Kenya, Libya, Malawi, Malaysia, Nepal, Niger, Nigeria, Pakistan, Sierra Leone, South Africa, Sri Lanka, and Zimbabwe. Having an appearance and density similar to that of water and frequently stored in unsecured ordinary beverage containers, kerosene is readily ingested by children. This risk is ironically compounded by lack of adequate illumination. In all 36 cases (51% of all child poisonings) reported in a Malaysian study (Azizi et al., 1994), kerosene was kept in a soft-drink bottle, typically on the kitchen floor. Most studies on poisonings in the developing world (such as Osaghae and Sule, 2013) have identified kerosene to be a leading cause of poisoning in children, ranging from 25% to 65% of all cases in the literature reviewed here.

According to one source (Nisa et al., 2010), ingesting as little as 1 ml of kerosene can cause complications, while 10 ml can be fatal. Common complications include respiratory effects and pulmonary damage. Additional impacts include gastrointestinal irritation, fever, central nervous system impairment, fever, myocarditis and leukocytosis. A broader literature review identified that the chemical form of pneumonia occurs in 12% to 40% of the cases (Carolissen and Matzopoulos, 2004).[10] Sufficient dosages can lead to coma and death. Among the particularly high mortality levels, a rate above 5% was observed in a six-year hospital study in Nigeria (Belonwu and Adeleke, 2008). There was a 7% average death rate (weighted by number of deaths) across 21 studies reporting mortality rates, with a large variance in outcomes across studies.

Illuminance levels and compromised visual performance

The illuminance levels recommended by professional illuminating engineering societies for electric lighting are 10 to 100 times greater than the levels provided by fuel-based lanterns (Mills and Borg, 1999).[11] A study of home lighting in a rural Nepali village led to recommended levels in the 5 to 15 lx (lumens per square meter) range for general-purpose lighting, primarily for cooking and socializing, and 25 lx for reading (Bhusal et al., 2010). These levels are still below the levels recommended by illumination engineering societies, but higher than the levels typically provided by fuel-based lighting. The dominant fuel type in the Nepali study was burning *jharro* (resin soaked pine sticks).[12] Interviews of a small number of fuel-based lighting users in the field indicate that night vendors find the illuminance levels from fuel-based lanterns inadequate (Alstone et al., 2010). Impaired visual performance (including disability glare) is, in turn, a risk factor in subsequent accidents and injuries. Similarly, inadequate illumination invites crime (Associated Press, 2013; UNDP, 2012; Peacock, 2013).

Insufficient illumination can lead to poor visual performance, fatigue and eyestrain. Research is inconclusive on whether sustained, insufficient illuminance levels and eyestrain contribute to myopia (nearsightedness) (Kittle, 2008; Gauna and Gauna, in press). A study of households using solid cooking fuels noted differences in cataract incidence depending on whether a home's light was provided by electricity or kerosene, with the risk twice as high for households using kerosene lighting (Pokhrel et al., 2005). The authors noted that the baseline incidence of cataracts is generally higher in developing countries and that more females than males are blind from cataracts, but there is no causal theory supporting a linkage with pollutants emitted during combustion. Cataract risks are wavelength-dependent, with ultraviolet being the most harmful, and, to a lesser degree, infrared. This author has not identified any studies that conclude that exposure to fuel-based lighting is a significant risk factor for cataracts.

In a recent set of interviews conducted by the author and colleagues, night fishermen in Tanzania reported multi-hour periods of reduced vision after each evening's handling of pressurized lanterns containing particularly bright mantles. Interviewers recorded self-reported claims of high incidence of blindness in old age (Mills et al., 2014). This purportedly resulted from repeated periods of close proximity to pressurized lanterns (which have 10 times the overall luminous output of typical wick lamps, from a mantle with very high luminosity). Eyestrain and poor eyesight attributed to glare and direct exposure to the luminance pressure lanterns are mentioned in other surveys conducted across sub-Saharan Africa (Baker and Alstone, 2011).

Reliable, high-quality illumination is essential for the effective delivery of health services. Many facilities in the developing world operate only intermittently at night due to fuel availability and the inability to provide good care with only lanterns (Solar Aid, 2012). Orosz et al. (2013) estimate that there are approximately 86,000 health clinics throughout the developing world that lack electricity, of which more than half are in Africa. Studies note that lack of light discourages some in-need populations from even attempting to visit a clinic or hospital at night. Lack of electricity also presents challenges for keeping mobile phones charged, equipment sterile, and powering key tools for communicating with patients and staff. The cost of kerosene is a hardship for many healthcare providers.

Disproportionate impacts on women and children

A consistent pattern that emerges from the available literature is that women and children bear the brunt of the health hardships

[8] Outlawed in the USA since 2003.

[9] As per Poppendieck et al., for outdoor-ambient conditions and indoor conditions with lamps, inhalation mass (versus absorbed dose) is based on the product of average inhalation rate 4.5 L/min, exposure duration (2.5 h per day for lamps, 10 h for ambient), and average measured particle concentration from Apple et al. (2010). Values for cooking were based on multiple filter measurements performed over periods of 8 to 24 h, with cooking occurring intermittently during those periods, assuming all particle mass was from stoves and that the occupant was inside while the cooking fuel was burning, evaluated at the aforementioned breathing rate.

[10] Kerosene ingestion accounted for a considerable proportion of all pediatric admissions at state hospitals across South Africa, ranging from 5.5% to 16.5% of all admissions, with markedly higher rates (up to 78%) in lower-income areas where kerosene is most widely used (Carolissen and Matzopoulos, 2004).

[11] Recommended levels of illumination are based on laboratory and field studies of specific visual tasks and visual performance needs. They may also consider glare, fatigue and eye strain.

[12] "*Jharro* is a resin rich oden stick from the high elevation Himalayan pine tree whose flame provides smoky but minimally adequate indoor lighting," according to Nepal's Rural Integrated Development Service. http://www.rids-nepal.org/index.php/Light.html.

associated with off-grid lighting (Alstone et al., 2011). For context, the rate of childhood unintentional injury deaths (from all causes) in the developing world is nearly four times that of the industrialized world, with 875,000 affected each year (Balan and Lingam, 2011) and with millions more sustaining non-fatal injuries. Anecdotal reports suggest sexual violence against women is higher when in sufficient illumination is provided in public areas (Associated Press, 2013; UNDP, 2012; Peacock, 2013).

The aforementioned problem of inadequate lighting in health clinics creates particular issues concerning maternal and infant health. Approximately 287,000 maternal mortalities occurred globally in 2010, 99% of which occurred in developing countries (World Health Organization, 2012a, 2012b). Two 2012 field studies document child delivery illuminated with kerosene lanterns or with light from makeshift, repurposed cell phones (Solar Aid, 2012; Statchel, 2012). In their analysis of the national household survey in India, Lakshmi et al. (2013) discovered an unexpectedly higher rate of stillbirths in women who rely on kerosene rather than electricity for lighting. An extensive study in India (Epstein et al., 2013) found that lower infant birth rates and higher neo-natal mortalities were associated with households that used kerosene as a cooking fuel. It is not clear whether kerosene combustion for lighting would yield the same outcome.

As noted above, the issue of non-intentional fuel ingestion almost uniquely impacts children, especially infants and toddlers, and is typically the primary cause of child poisoning in the developing world.

Studies of lamp explosions due to fuel adulteration found up to two-fold higher impacts among children than adults: 62% versus 38% injury (Grange et al., 1988) and 57% versus 25% mortality (Ugburo et al., 2003). Female to male ratios were also higher in each of three studies providing such data (Table 2).

Lighting-related burn injury rates are higher for females and children across many studies (Balan and Lingam, 2011), with one study finding a 3:1 ratio in India (Kumar et al., 2000). Functional, social, and psychological impairment due to burns has been identified as one of the most devastating causes of child injury. In a nationwide study for Bangladesh, in which 171,000 households were visited, rural children were found to have a four times greater incidence of burn than those in urban areas; and, kerosene lamps were responsible for 23% of burns sustained by infants and 11% for children aged one to four years (Mashreky et al., 2008). In the same study, burns were the fifth leading cause of illness among the children aged one to 17 years of age, and the third leading cause for children aged one to four. Particularly tragic fires such as one in Senegal (where at least 9 children died when a candle fell over) involve indentured children or orphans that were confined without an opportunity to escape (Nossiter, 2013). Burns from all causes are reported as the leading cause of death among children in South Africa (Mmathabo and Dhlamini, 2008).

To the extent that women and children spend more time indoors than men—and that children are intrinsically more vulnerable to hazards—they are differentially exposed to indoor air quality, fire, and lamp-explosion risks. A study of 345 people in 55 Kenyan households found that children of each gender up to the age of four spend roughly equal times indoors. However, females in all other age groups spend between one and 4 h more per day indoors than males do (Ezzati and Kammen, 2002). Males spend less overall time indoors than these other groups. A major study of 4612 individuals drawn from representative locations in Bangladesh found that infants spend the most time indoors: approximately 20 h per day, declining to 16 h per day for individuals up to the age of 60. After age 60 females' time indoors returns to a level of nearly 20 h per day, while time spent indoors by males increases only to 16.5 h per day. All groups of females over the age of 12 spend more time indoors (1.4 to 3.2 h more per day) than do males. The Bangladesh study concluded that "young children and poorly-educated women in poor households face [indoor air] pollution exposures from cooking that are four-times those for men in higher-income households organized by more highly educated women," with half of the effect due to income and half to age and gender (Dasgupta et al., 2006). Data indicating location by time of day (and use of lighting by time of day) would be needed to determine if lighting-related emission exposures differ materially among these groups. Men and children not participating in cooking activities will receive a larger share of their indoor air pollution exposures from lamps.

Table 2
Illustrative "epidemics of kerosene disasters" caused by fuel adulteration.

Year	Location	People injured/killed [female:male]	Source
1984	Lagos, Nigeria	53/30 [1.9:1][a]	Grange et al. (1988)
1994	Rajasthan, India	303/37	Gupta et al. (1996)
2001	Lagos, Nigeria	116/18 [1.5:1]	Oduwole et al. (2003)
2001	Lagos, Nigeria	59/35 [1.3:1]	Ugburo et al. (2003)
2001	Madang, Papua New Guinea	38/5	National Disaster Management Office (2001)
2004	Edo State, Nigeria	2500/368	Bernard (2011)
2007	Delta State, Nigeria	22	Onoyume et al. (2007)
2011	Port Harcourt, Nigeria	1/5	Nigeria News (2011)
2011	Edo State, Nigeria	1/8	Daily Independent (2011)
2011	Duhbri, India	62/8	The Telegraph (2011a, 2011b)
2012	Edo and Delta States, Nigeria	11/11	Tamuno (2012)

[a] Ratio in the month of burn disaster (March). Ratio 1:1 in earlier periods.

Alternatives to fuel-based lighting

Health benefits of introducing solar-LED lighting systems

Substantial and diverse health and safety risks posed by fuel-based lighting can be reduced through the substitution of non-combustion lighting technologies (Kimemia et al., 2014). In addition to improved health outcomes are multiple benefits of addressing these risks. In particular, eliminating fuel-based light sources would also reduce poverty and deliver a significant reduction in greenhouse-gas emissions (Mills, 2005), while supporting new forms of employment (Mills, forthcoming-b), and weaning governments off the burden of fuel subsidies that often exceed expenditures on healthcare (Mills, forthcoming-a).

Grid electrification programs have attempted to displace lighting fuels for decades, but in most places the rate of progress lags even the rate of population growth. In some parts of the world, particularly sub-Saharan Africa, the number of people using fuels for lighting is still increasing. A far more promising, affordable, and scalable approach for energy access is the use of small-scale solar or grid-charged LED lighting systems, many of which provide more, better, and safer light at a lower total cost of ownership (see Mills, 2005). Many examples have been documented.[13]

Available accounts of benefits are based on end-user reports, rather than rigorous independent studies. A field study of 500 homes in the Philippines observed near complete elimination of reported health and injury issues following replacement of kerosene lanterns with grid-independent LED lanterns (Fig. 3).[14] A study of 209 households in

[13] Numerous case studies are documented on LuminaNET: http://luminanet.org/page/field-projects-directory.

[14] In this report, the shorthand term "LED lantern" is used to describe a broad category of lighting products that have emerged over the past decade. Common attributes are: high-efficiency "white" LED light sources; compactness and portability; a battery or other form of storage that allows grid-independent operation, charging either from dedicated renewable (typically solar ~10 peak Watts) power source or a temporary grid connection (as mobile phones are charged); a larger degree of affordability than first-generation fluorescent devices; and they are "plug-and-play", i.e., no need for professional installation. Within these broad criteria are found many variations including light output (level and directionality), charging time, battery life, and, the presence of secondary functions such as phone charging. Quality also varies widely and those considered viable alternatives to fuel-based lighting have high levels of performance and truth-in-advertising such as those recognized by the Lighting Global product quality assurance program. There is no consensus on terminology, and descriptors such as lamp, lantern, torch, light, and pico power will often be used to describe some or all of the products in this category.

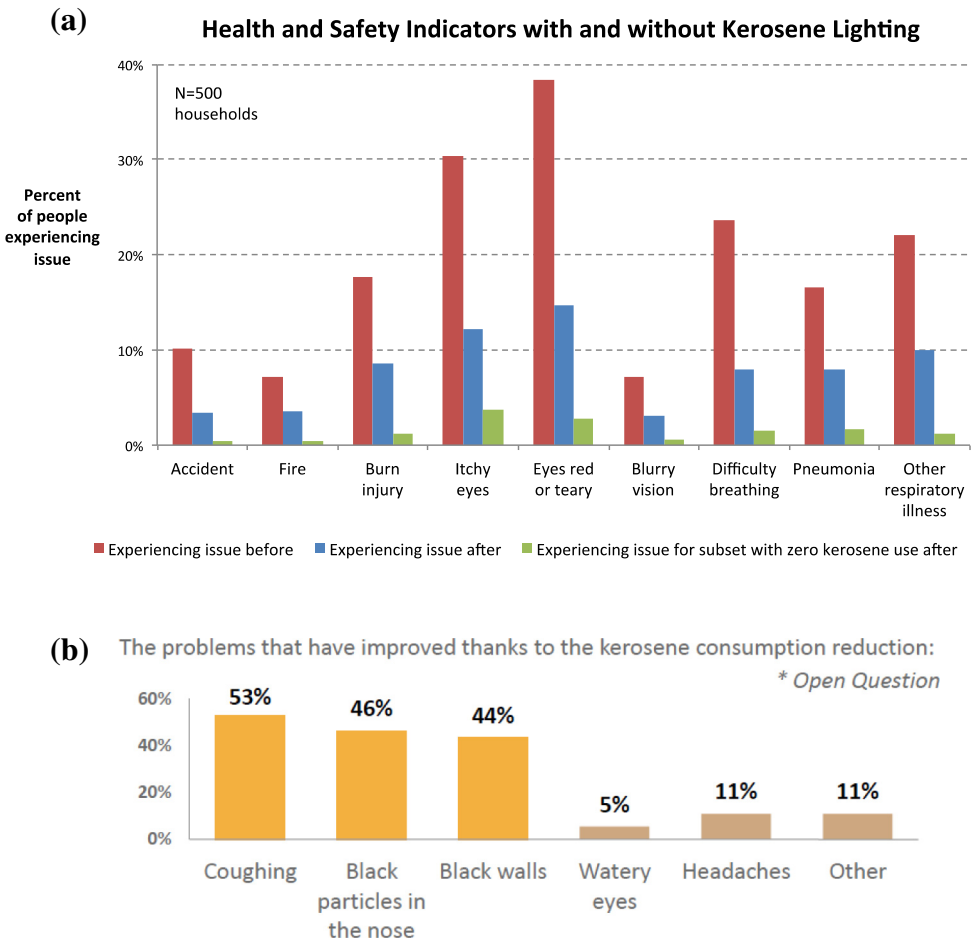

Fig. 3. a and b. Data from the Philippines. (a) Changes in user-reported health and safety problems believed to be associated with kerosene lanterns before and after receipt of LED-solar replacements among 500 homes in the Philippines (Thatcher, 2012). Recipients were re-interviewed one month after receiving the fuel-free lamps. Note that 66% of the homes still used some kerosene after the intervention (blue bar). Symptoms were reduced much farther among the 27% of homes that completely eliminated kerosene use. (b) Separate study, 109 households reporting. (For interpretation of the reference to color in this figure legend, the reader is referred to the web version of this article.)

Ghana found that a far higher rate (89%) of households using only kerosene for lighting reported having blackened nostrils (from soot) in the mornings than those using a mix of kerosene and solar lighting (24%) (Obeng et al., 2008). A survey of 500 homes in Uganda found an 88% reduction in burns and a 93% reduction in house fires after receiving solar lanterns (Shell Foundation, 2015).

Refugee camps are particularly at risk for destructive fires caused by lanterns, as well as violence against women and children at night. For security and safety, lighting is an essential service. The UN High Commissioner on Refugees has initiated efforts to introduce solar lighting, with 60% of people reporting improved safety at night (UNDP, 2012; UNHCR, 2012).

Solar Aid installed 30 solar electricity and lighting systems in rural health facilities in Tanzania (Solar Aid, 2012). Preliminary results found reduced rates of infection (including HIV); these outcomes were attributed to better illumination and associated ease of maintaining sanitation. Longer and more consistent operating hours reportedly induced more individuals to seek health care rapidly and more mothers to give birth in clinics. This improved access to services at night led to reduced patient waiting times during the day. Patients cited the benefit of not being expected to bring their own lantern and/or fuel to ensure treatment at night. The study claims a "clear increase" in safe baby deliveries at night, improved detection of postpartum hemorrhage, tears, or problems with the baby. Staff accounts indicated improved morale among hospital staff.

In a larger trial by Solar Aid, light was brought to clinics in Malawi, Tanzania, and Zambia that serve over 5000 patients per month (Solar Aid, 2011). Non-specific improvements to security and morale among workers and patients were reported to translate into a higher quality of service and better engagement of both staff and patients.

Nigeria has one of the highest maternal mortality rates in the world. One company has completed solar lighting installations at 26 Nigerian healthcare locations (along with power for cell phones and fetal monitors) (Stachel 2012). All locations reported a higher proportion of mothers coming to clinics for delivery, particularly night deliveries. Lighting provided particular benefits for complicated deliveries. Reliable illumination allowed for an increased rate of cesarean section surgeries to be performed at night. Blood bank procedures were also improved via increased ease and accuracy for testing the blood, together with refrigeration. Every site reported an improvement in health worker morale and willingness to come to work at night. Similar work was conducted in Sierra Leone, which has more than 1000 non-electrified rural clinics (Stachel, 2013).

Health considerations of alternatives to fuel-based lighting

A switch to electric lighting is the most promising pathway for fully eliminating the risks associated with fuel-based light sources. Nonetheless, the generation and distribution of electricity are not risk-free, particularly when electricity is produced with fossil fuels or

nuclear fission. Second-order issues such as the diversion of scarce water for power plant cooling and the concerns associated with electricity transmission lines should also be considered. Distributed renewable energy based generation mitigates most of these supply-related concerns.

Off-grid lighting systems based on renewable energy sources require some form of energy storage, typically batteries that can have associated health and safety risks. These end-use illumination devices may contain potentially harmful substances, for example, mercury-containing lamps. From a lifecycle perspective, the environmental and health implications of the energy embodied in creating electric lighting systems must be considered. Solar-LED lanterns have been found to save far more energy than that embodied in their manufacture (Alstone et al., 2014).

First-generation electric off-grid lighting systems relied on large solar panels, large lead-acid batteries (used in a context in which there was rarely a process for recovery, recycling and reuse), and mercury-containing fluorescent lamps. Fortunately, the rapid transition in the past decade to highly miniaturized pico-photovoltaic systems has dramatically reduced the physical amounts of materials involved as well as waste-management concerns. Mercury-containing lamps have been displaced by higher efficiency light emitting diode (LED) lamps. Due to reduced power requirements, the batteries and solar panels can be far smaller, with correspondingly lower material inputs. The off-grid lighting product industry is making a rapid transition to lower environmental impact technology. For example, the share of lithium-ion batteries used in off-grid lighting products rose from 5% in 2010 to 40% in 2012, while the shares of lead-acid batteries fell from 35% to 27% (Lighting Africa, 2013).

New off-grid lighting products should be designed so that they do not compromise visual performance or health. For example, LED lanterns can be designed with shields to reduce glare. Commonly used low to mid-power white LEDs, the preferred light source for off-grid applications, are not regarded as eye safety risks (USDOE, 2013). Most white LEDs do not emit ultraviolet or infrared radiation; however, blue wavelengths (in high color temperature lamps), if delivered with high power and intensity, can damage the retina. When a set of products geared for the off-grid market were tested using the IEC 62471 safety test protocol, one barely entered the "moderate risk" level after 58 s of exposure (Lighting Global 2013). This occurred under a worst-case test condition (holding the LED as close as possible to the eye while remaining in focus). These risks can be eliminated, and glare significantly reduced (and thus light *quality* increased), by utilizing a diffusing lens or material in front of the LED. Bluish light may also disrupt circadian rhythms, although this has not been attributed to LEDs thus far. LEDs are available that provide "warmer" ("lower color temperature" illumination). While low-light conditions can cause temporary eyestrain and perhaps nearsightedness over a long timeframe, off-grid LED systems will virtually always provide higher light levels than the flame-based products they replace. Care should be taken to develop minimum illuminance standards and best practice application guides for these products.

Policy strategies

Fuel-based lighting is associated with a strikingly wide array of health and safety risks. The underlying drivers are many, with no single solution. Other authors have enumerated the causal factors, low levels of risk perception among at-risk populations, and available prevention strategies (Paraffin Safety Association, 2004; Schwebel et al., 2009a, 2009b; Mmathabo and Dhlamini, 2008; Swart and Bredenkamp, 2012).

Approaches for better understanding the risks and reducing lighting-related injuries and loss of life can be grouped into the following broad categories.

More robust national-level baseline data on lighting fuel choices, using clearly defined and consistent definitions

- Baseline data are essential to identifying overall populations at risk, and the associated geographies. Better country-level data on the incidence of fuel-based lighting (including non-household contexts and among electrified populations) and the fuels used to do so are key needs. A particular information deficit includes the degree to which cooking fuels are used to provide light after cooking tasks are complete.
- Time-budget data are critical to understanding not only total hours spent indoors (important for assessing exposure to risks from cooking risks), but also what portion of that time is during hours where artificial lighting is in use.
- The degree of substitution achieved when electric alternatives are introduced is important information for determining residual risks where replacement technologies have been deployed.

More lab-based research on lighting technology characteristics

- Most testing of the emissions from fuel-based lighting equipment has focused on kerosene lamps. To this should be added diesel, animal and vegetable oils, dung, and fuel wood. Emissions from each will have unique chemical constituents and levels of particulates.

More rigorous and focused field-based epidemiological studies investigating risks and the potential benefits of alternatives

- The literature on this topic is new in the broader context of health and development research, and its quality is uneven. Systematic national or community-scale epidemiological information on lighting-related risks in the developing world is rare, with Ghana and South Africa making the greatest progress to-date in this respect. More centralized statistics should be gathered, per standardized methods, and used to better understand population-level risks.
- Moreover, most existing studies fail to separate lighting fuels from other sources of energy-related exposures and risk. A review of the relatively large body of literature on cooking-related risks may provide some lighting-related contextual information collected that would be useful. VanVliet et al. (2013) provides one example of a study that gathered and analyzed such information.
- Several studies have tabulated user-reported reductions in symptoms or safety outcomes when solar-LED lighting has been introduced, but no scientifically rigorous assessments have been reported.
- Substantial and enduring mental and emotional injury may also result from lighting-related accidents, adding to health costs, lost work time and lowered productivity, and replacing damaged homes and property. The literature does not systematically address such crucial impacts that follow the initial acute consequences arising from the off-grid lighting hazard.

Improved consumer education, standards, and supporting energy policies

- Health and safety education is a critical need. For literate user groups (a subset of the overall population at risk), product labeling and other safety warnings could help reduce incidence of injury and death from fuel-based lighting. Other media, such as radio programs or in-person community health presentations, can also deliver safety information and introduce information about safer off-grid products. Such efforts, however, will not reach many populations.

- Although one in five people in the world are exposed to indoor pollution from fuel-based lighting on a daily basis, only World Health Organization guidelines exist for certain associated pollutants. Few national governments recognize that indoor air pollution is a public health concern that merits high priority. This gap must be bridged.
- Regulation and oversight of fuel handling, and more strict consequences for fuel adulteration, may reduce (but not eliminate) the life-threatening practice of mixing other fuels with kerosene. Energy price subsidy practices contribute to this problem, and thus subsidy reform is a tool for reducing this particular risk.
- Kerosene has long been subsidized and represented as a "clean" or "healthy" fuel when used instead of biofuels. However, these subsidies undermine the cost-effectiveness of substituting non-combustion lighting systems, while extending kerosene supply for cooking purposes works as cross-purposes from eliminating it for lighting purposes.

Transition to alternatives to fuel-based lighting, to reduce health and safety impacts

- Any prospective change in lighting technology should be assessed in terms of health and safety risks. Combustion emissions, injury risk, and visibility-safety risks should all be assessed. Work is ongoing to assess the adequacy of illumination levels for poor populations who cannot afford lighting systems that replicate the levels of illumination expected by affluent societies.
- Cleaner-burning and shielded kerosene or propane lanterns are substantially more expensive to purchase and operate than standard exposed-wick lamps, further limiting their potential. Kerosene can be easily colored to help distinguish it from water, but this precaution does not prevent ingestion by young children. Some organizations have promoted improved fuel-based lanterns (WHO and UNICEF, 2008). This, however, addresses fire risk at best, while doing little to address indoor pollution, child poisoning by ingestion of fuel, fuel-adulteration hazards, and emissions of greenhouse gases.
- Fossil fuel-based lighting technologies can, to some extent, be re-engineered, for example, to reduce tip-over risks of lanterns, improve combustion efficiency, or eliminate lead from candle wicks. However, many fuel-based lighting devices are hand-manufactured using discarded metal or glass containers, severely limiting any affordable opportunity for a centralized solution.

Conclusions and recommendations

The diverse morbidity and mortality risks of fuel-based lighting suggested by the literature include: burns (arising from structure fires as well as explosions from adulteration of kerosene with other fuels); health risks from indoor air pollution; poisoning from non-intentional ingestion of kerosene; compromised visibility and visual health; a variety of health and safety issues; and, adverse or suboptimal outcomes in health-service facilities illuminated solely or sporadically with fuel-based light. These impacts are experienced disproportionately by women and children.

Replacement of intrinsically dangerous fuel-based technologies with off-grid LED lanterns is the most promising way to eliminate the myriad risks of lighting fuels. It reduces the cost of lighting as well, thereby supporting broader goals to alleviate poverty. It is encouraging that a wide variety of effective and affordable technologies have recently emerged in the market. A host of policy strategies are being brought to bear to accelerate the uptake of these alternatives to fuel-based lighting. In addition to displacing hazardous lighting practices, these new technologies also enable the introduction of light into areas that are presently not lit at all, in turn enhancing safety in a variety of ways.

Policies and programs seeking the greatest possible benefit should target the most impacted geographical and demographic user groups. Examples include improved illumination in healthcare facilities, substitutes for kerosene lighting where housing is dense and poorly defended from fire (slums) and where fuel adulteration is particularly common due to fuel subsidy imbalances and other factors. Systems such as South Africa's mapping of fuel-related injuries could be emulated to deploy targeted programs for grid-independent electric lighting replacements for fuel-based lighting. Improved technologies for women and children will yield particularly significant health benefits.

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