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Solid Fuel Use: Health Effect

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Abbreviations

ALRI	acute lower respiratory infections
COPD	chronic obstructive pulmonary disease
GNI	gross national income
LPG	liquefied petroleum gas
PM	particulate matter
PM_{10}	particulate matter of a diameter of up to 10 micrometers
$PM_{2.5}$	particulate matter of a diameter of up to 2.5 micrometers
WHO	World Health Organization

Introduction

Globally, more than 3 billion people depend on biomass and coal to meet their basic energy needs for cooking, boiling water, lighting, and, depending on climatic conditions, space-heating. The use of these solid fuels on open fires or inefficient stoves results in large amounts of a range of health-damaging pollutants, often under conditions of poor household ventilation. For more than half of the world's population, meeting daily household energy needs can therefore represent a substantial threat to health. It primarily affects developing countries, but marginalized populations in industrialized countries may also be concerned. Women and young children, who may spend many hours in the vicinity of the smoky hearth, are most at risk.

The earliest systematic studies to quantify exposures among women in rural India in the early 1980s reported pollution levels more than an order of magnitude higher than those commonly found in cities with high levels of ambient air pollution. The first epidemiological field studies of health effects from cooking with biomass were conducted in Nepal. In the mid-1980s, the World Health Organization (WHO) began to take notice of the problem, and a full environmental health analysis, which laid out the problem in terms of source, emissions, concentrations, exposures, doses, and health effects, was published shortly afterward. As a result of these early analyses, the United Nations Environment Programme called attention to exposure to solid fuel use as the most important global health impact related to women's work, and, in its contribution to the Rio Earth Summit in 1992, the World Bank termed it one of the four most important environmental hazards in the world.

Since the early 1990s, an increasing number of more sophisticated epidemiological studies have linked exposure to indoor air pollution from solid fuel use to a wide spectrum of health outcomes. These include pneumonia among children and chronic obstructive pulmonary disease (COPD) and lung cancer among adults, as well as other types of cancers, tuberculosis, cardiovascular disease, adverse pregnancy outcomes, asthma, and cataracts. In addition, traditional household energy practices have other negative consequences for health, safety, and well-being.

This article presents an overview of global and regional household energy practices, considers the composition of biomass smoke and coal smoke as well as associated pollutant concentrations and personal exposure, and reviews the evidence linking indoor air pollution to a variety of health outcomes. Based on the assessment of the burden of disease attributable to indoor air pollution from solid fuel use, it discusses the public health significance of this environmental health risk and its broader consequences for economic development and environmental sustainability in developing countries.

Solid Fuel Use and Household Energy Practices

Assessment of Solid Fuel Use

It is known that many poor households rely on more than one fuel type, depending on the type of food prepared and food availability, season, and other factors, but such detail is not systematically available across the world. The WHO is the agency monitoring the core health and development indicator "proportion of population using solid fuels," which can be interpreted as relying primarily, but not necessarily exclusively, on coal, charcoal, wood, crop, or other agricultural waste, dung, shrubs, grass, and straw. Electricity, natural gas, liquefied petroleum gas (LPG), biogas, and in rare cases, modern biofuel such as ethanol or plant oils are considered cleaner fuels. It is difficult to take a clear health position on kerosene (also referred to as paraffin). Although its use in well-operating stoves results in much lower emissions than emitted by solid fuel, poorly operating stoves can lead to high pollutant concentrations and there is some concern about the unsafe storage and use of kerosene leading to burns, fires, and child poisonings.

For a majority of developing and middle-income countries, data on the main type of cooking fuel are compiled from household surveys or censuses; where such information is not available at the national level, data are modeled based on the proportion of people living in rural areas and the gross national income (GNI). For upper-middle or high-income countries with a GNI of more than US$10 500 per capita, national solid fuel use is assumed to be below 5%. The latest comprehensive assessment indicates that in 2003 52% of the world's population were using solid fuels to meet their household energy needs. This percentage varies widely between countries and regions (Figure 1); sub-Saharan Africa, South East Asia, and the Western Pacific region are most affected (Figure 2). Overall, wood is the most widely used solid fuel; coal is highly prevalent in China but does not substantially contribute to national household consumption in other developing and middle-income countries.

Trends in Solid Fuel Use

Current databases and associated models do not allow trends to be estimated with precision. Over the past decade there has been an indication of a steady drop in the percentage of households relying on solid fuels, accompanied by a slow rise in the total population affected because of population growth. Assuming a business-as-usual scenario where the observed annual increase in the number of people with access to cleaner fuels between 1990 and 2003 is applied to the period 2003–2015, the number of people using solid fuels will remain practically unchanged in the coming years (third bar from left in Figure 3) and up to 2030. In general, when socioeconomic circumstances improve, households tend to move up the energy ladder: that is, they gradually conduct more of their household energy activities with progressively cleaner, more efficient, and more convenient fuels (Figure 4). The recent rapid rise in petroleum prices, however, may result in a substantial shift down the energy ladder to biomass fuels, as populations find LPG and kerosene too expensive.

In stark contrast to the predicted trend, the United Nations Millennium Project has called on countries to adopt the voluntary cooking energy target "by 2015, to reduce the number of people without effective access to modern cooking fuels by 50%, and make improved cookstoves widely available"; its achievement is considered an essential contribution to the Millennium Development Goals. For this target to become a reality, 1.7 billion people will need to gain access to LPG, natural gas, electricity, biogas, and other modern fuels (fourth bar from left in Figure 3). Even reaching this ambitious target, however, would still leave 1.5 billion people cooking with solid fuels in 2015.

Household Energy Practices

The extent of exposure to indoor air pollution due to combustion of solid fuel is determined by several parameters, in particular fuel type, stove type, and ventilation. Although simply enclosing the fire does not guarantee better combustion, a number of different enclosed stove designs burn fuel more cleanly and efficiently than an open fire or open stove. With a suitably designed, built, and operated flue (chimney) or hood, much of the pollution is released outside. Population-based estimates of cooking and heating practices are limited, but data from the World Health Survey suggest that more than 90% of homes using biomass for cooking do so without a chimney or hood. The resulting exposure also critically depends on the location of the stove (inside or outside, for example) and the ventilation of the household (many open windows, for example) – parameters that are not well characterized globally.

Sociodemographic and behavioral factors may matter almost as much in determining exposure as the choice of fuel and appliance. Concentration of the particulate matter (PM) in household smoke is significantly correlated with kitchen location, fuel quantity, and ventilation practices. Family members have different levels of exposure depending on the time they spend in different more or less polluted parts of the home and the extent to which they do the cooking, or are kept close to the fire during cooking in the case of small children.

Finally, in many societies, fuels are used for a variety of household-based activities other than cooking, such as lighting, cooking animal food, boiling water, space – heating, and various forms of income generation, such as ceramic or food preparation businesses. Each of these may represent a source of household air pollution, potentially aggravated by cultural practices, such as brewing and distilling alcoholic beverages in a variety of countries or the use of a wood-fired sauna, the *temascal*, in Central America.

Socioeconomic and Urban–Rural Variation in Solid Fuel Use

Clear urban–rural differences in household energy practices are apparent. In many of the poorer countries of sub-Saharan Africa and South Asia, close to 100% of rural dwellers rely nearly exclusively on gathered wood, dung, or crop waste. Biomass fuels are still widespread in urban areas but often need to be purchased, which helps drive progression toward replacement by higher quality commercial fuels, such as charcoal, LPG, and kerosene, at least among better-off urban groups. Similarly, marked socioeconomic differences, indicated by

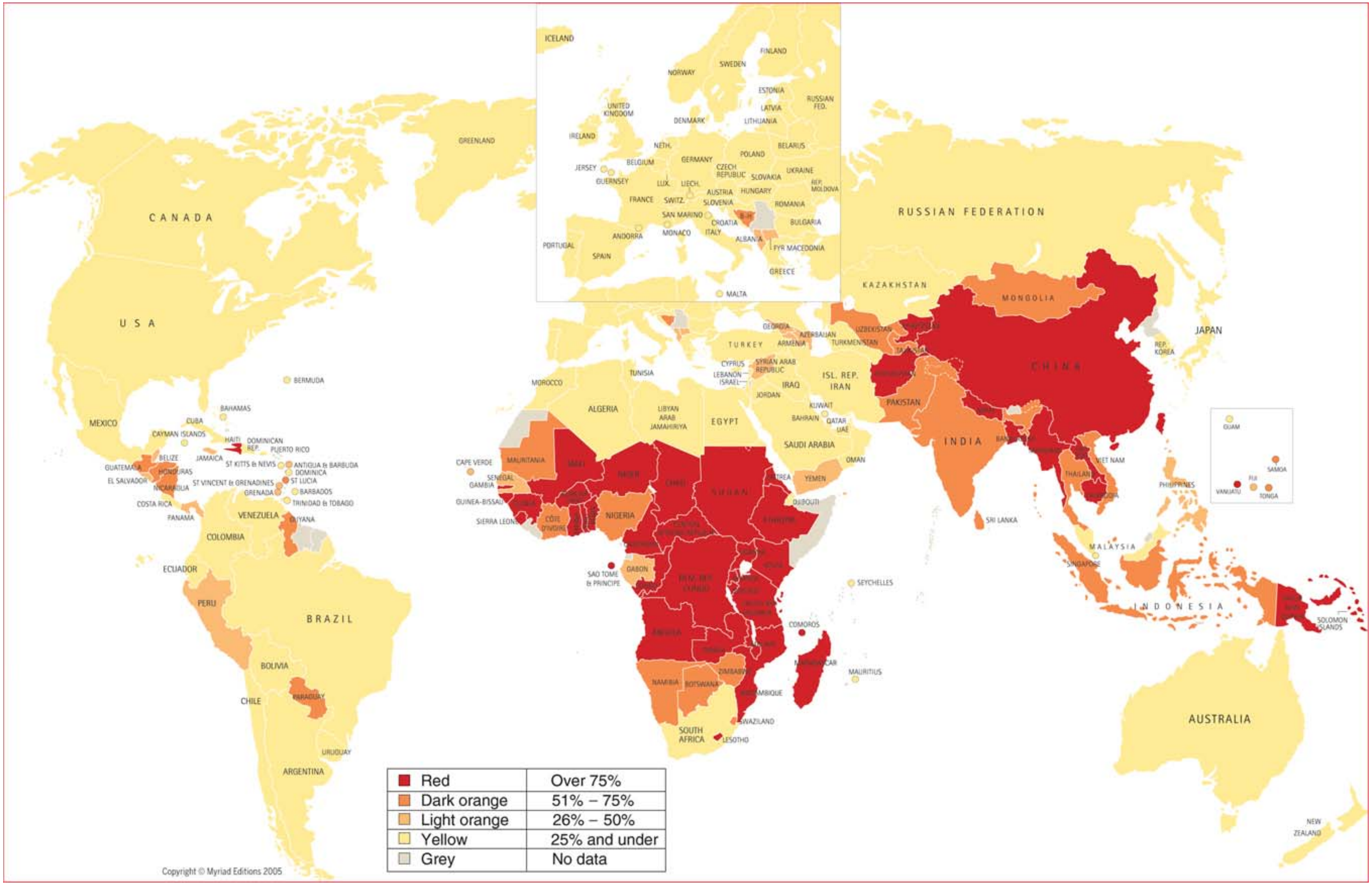


Figure 1 Percentage of population using solid fuels: 2003 or latest available data.

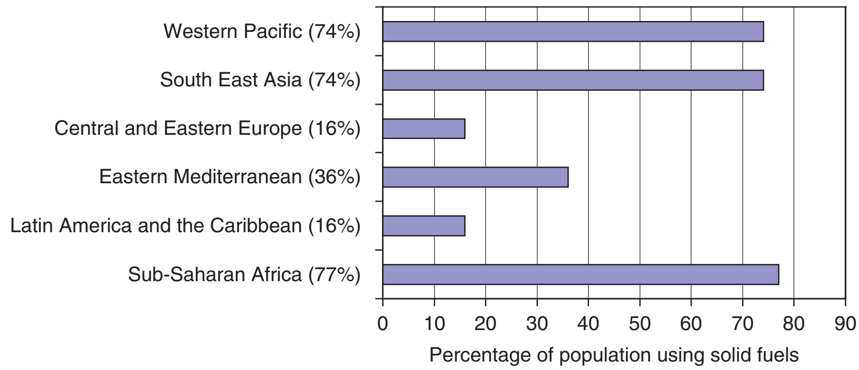
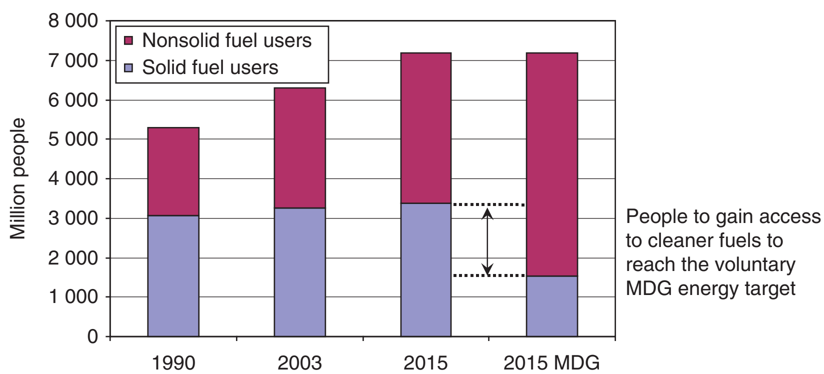


Figure 2 Solid fuel use in developing regions (2003 or latest available data).



Data for 2015 are based on:

- a business-as-usual scenario that applies the observed annual increase in the number of people with access to cleaner fuels from 1990–2003 to the period 2003–2015;
- the voluntary Millennium Development Goal (MDG) target proposed by the UN Millennium Project to halve the number of people without access to modern cooking fuels between 1990 and 2015.

Figure 3 Population using solid fuels (millions): 1990, 2003, and 2015.

wealth quintiles, are observed in both urban and rural settings (Figure 5(a) and 5(b), respectively).

Pollutant Concentrations and Personal Exposure

Emissions and Pollutants

The burning of solid fuels on open fires or traditional inefficient stoves generates hundreds of so-called products of incomplete combustion in the form of gases and aerosols (suspended liquids and solids). These include PM, carbon monoxide (CO), nitrogen oxides, sulfur oxides, polyaromatic and other hydrocarbons, and various organic substances. Charcoal combustion is characterized by lower levels of particulates and organic gases but higher levels of CO than wood. Even though biomass combustion depends on fuel type and combustion conditions, PM and CO are considered reasonable indicator pollutants for estimating many types of health risk from the complex mixture of pollutants emitted.

The amount and characteristics of pollutants produced during coal burning are highly heterogeneous. In addition to the above-mentioned products of incomplete combustion, coal burning releases increased concentrations of sulfur oxides and may contain toxic elements. It has been estimated that more than 2 million people in China suffer from skeletal fluorosis, in part resulting from the use of fluorine-rich coal, with many tens of millions experiencing dental fluorosis. Arsenic, another contaminant of coal in parts of China, is a well-known toxic element and has been associated with an increased risk of lung and other cancers.

Woodsmoke emission studies indicate that household cooking on open fires must also be associated with significant exposures to a range of toxic pollutants. These

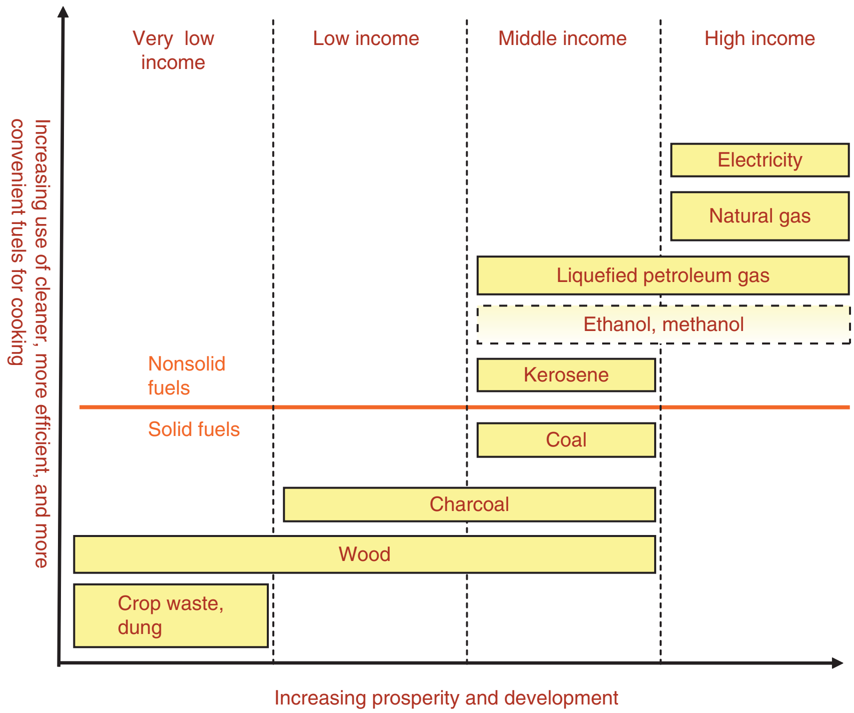


Figure 4 Energy ladder.

include chemicals usually considered to be industrial or modern pollutants, such as benzene, formaldehyde, benzo [a] pyrene and other polyaromatic hydrocarbons, 1,3-butadiene, and dioxin, many of which are known cilia toxins, mutagens, immune system suppressants, severe irritants, inflammation agents, central nervous system depressants, neurotoxins, and carcinogens. This review focuses on PM and CO, as has most research to date. Nevertheless, there is considerable scope for future studies to investigate the exposures and effects of these other pollutants on, for example, cancer, poor reproductive outcomes, and birth defects.

Mechanisms

Particles are generally classified according to their aerodynamic properties, as these determine transport and removal processes in the air, as well as deposition sites and clearance pathways in the respiratory tract. PM_{10} (PM with a diameter of up to 10 μm) represents the most widely used indicator of indoor air pollution in developing countries; $PM_{2.5}$ (fine particles with diameter up to 2.5 μm) is likely to have the greatest impact on respiratory health, as it is filtered only to a limited extent by the naso-oropharangeal region and can penetrate into the bronchial and alveolar regions.

There are abundant mechanisms through which particles may adversely affect the respiratory and cardiovascular systems as well as immunologic and inflammatory responses. Besides bronchial irritation, particles could increase the risk of disease by impeding specific host immunity, such as aspects of humoral and cellular immunity, and nonspecific host defenses, such as mucociliary clearance and phagocytosis. Ultimately, the oxidative activity of PM can lead to inflammation and tissue injury in the lung. Indoor air pollution has also been shown to result in the disturbance and reduction in the levels of different classes of serum immunoglobulins among neonates.

Carbon monoxide is a colorless, odorless, and tasteless gas. After reaching the lungs, it diffuses across the alveolar and capillary membranes into the bloodstream, where it binds to hemoglobin to form carboxyhemoglobin; the affinity of hemoglobin for CO is 200–250 times greater than that for oxygen. As a consequence, oxygen delivery to key organs, such as the brain, cardiovascular system, heart, and skeletal muscle as well as the developing fetus in pregnant women, is reduced, leading to tissue hypoxia. At high concentrations, CO can also bind to other heme proteins such as myoglobin and cytochrome oxidase. The dose-dependent and highly toxic effect of acute CO exposures is well understood, but relatively little is known about the health impacts of prolonged CO exposures.

On the basis of sufficient evidence in both humans and experimental animals, the International Agency on Cancer Research recently concluded that indoor emissions from household combustion of coal are carci

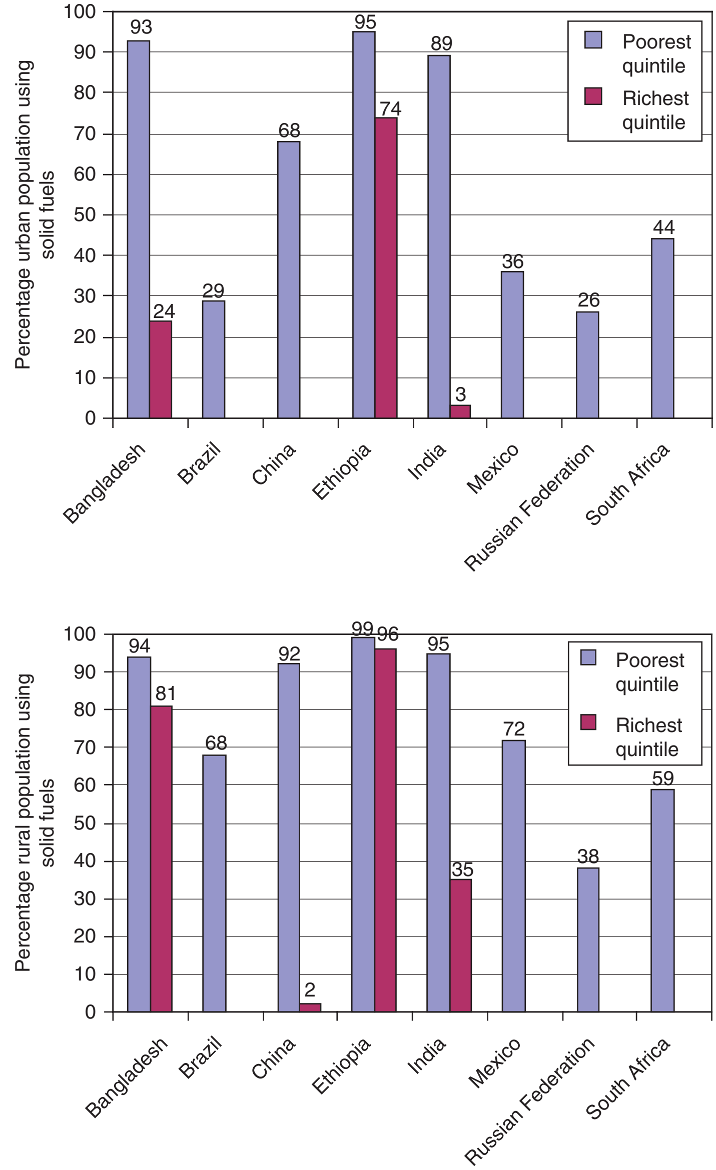


Figure 5 Percentage of population using solid fuels.

'nogenic to humans. Indoor emissions from household combustion of biomass fuel are probably carcinogenic to humans on the basis of limited evidence of the carcinogenicity of emissions in humans and animals, sufficient evidence of carcinogenicity of wood-smoke extracts in experimental animals, and strong evidence of mutagenicity.

Range of Concentrations

Based on a WHO database containing information from more than 70 published studies in developing countries, the average 24 h PM_{10} concentrations in solid fuel-using households range from 300 to 3000 $\mu g\,m^{-3}$. During cooking, levels of indoor air pollution can be as high as 30 000 $\mu g\,m^{-3}$. Annual averages have not been measured directly, but as cooking and other household energy practices tend to take place almost every day of the year, 24 h concentrations can serve as a reasonable estimate of annual averages. By comparison, the recently published WHO global air quality guidelines recommend that 24 h and annual mean concentrations of PM_{10} should not exceed 50 and 20 $\mu g\,m^{-3}$, respectively.

Based on the above-mentioned database, CO concentrations typically show 1 h averages of approximately 50 $mg\,m^{-3}$ (ranging from 9 to 263 $mg\,m^{-3}$) and 24 h averages of approximately 10 $mg\,m^{-3}$ (ranging from 2 to 14 $mg\,m^{-3}$). Relevant WHO guideline values for CO are

100 mg m^{-3} for 15 min, 60 mg m^{-3} for 30 min, 30 mg m^{-3} for 1 h, and 10 mg m^{-3} for 8 h. Acute exposures to CO in solid fuel-using homes may thus regularly exceed current guideline limits.

Personal Exposure among Women and Children

The indoor environment is the microenvironment in which most people spend the major fraction of their daily time. As a result, indoor air pollution levels contribute to population exposures more than those outdoors, although of course being influenced by pollution sources located indoors as well as outdoors. Women and young children, often carried on their mother's back, tend to be most exposed to smoke from solid fuel combustion because of women's nearly universal role as household cook and caregiver.

Exposure to air pollution can be estimated by measuring indoor pollutant concentrations combined with time-activity information. It is, however, better to measure personal exposure directly by using devices worn by the population of concern as they go through their daily activities. These various methods indicate that personal 24 h PM_{10} exposures for cooks range from several hundred micrograms per meter cube to more than $1000 \mu\text{g m}^{-3}$, with even higher exposures during cooking. Monitoring the personal exposure of young children is difficult, but a few such studies have been conducted in rural Guatemala and urban Ghana; one of the Guatemalan studies found $PM_{2.5}$ exposures among children to be a little lower than those of their mothers. The reductions in personal exposure that can be achieved when an open fire is substituted with a well-functioning chimney stove, or when users switch from biomass fuels to cleaner fuels are discussed elsewhere in this volume.

Health Outcomes Associated with Indoor Air Pollution

Levels of Evidence for Different Health Outcomes

In the context of WHO's comparative risk assessment, a systematic review of the evidence was conducted; the findings are summarized in Table 1. As will be further discussed in sections 'ALRI, COPD, and lung cancer,' this review concluded that there is strong support for a causal link with acute lower respiratory infections (ALRI) in children under five years of age, COPD in adults, and lung cancer in relation to coal use in adults. Owing to the paucity of epidemiological studies in developing countries, evidence for a causal link between indoor air pollution exposure and lung cancer in relation to biomass use as well as other types of cancer, tuberculosis, asthma, cataracts, various adverse pregnancy outcomes, interstitial lung disease, and cardiovascular disease was considered inconclusive and deemed insufficient for inclusion in the burden of disease calculations.

Several more recent studies conducted in Guatemala, India, Southern Pakistan, and Zimbabwe provide additional support toward an impact of indoor air pollution on birthweight, stillbirth, and perinatal mortality. These findings are backed by a growing literature in industrialized countries that exposure to air pollution increases the risk of preterm delivery and other adverse perinatal outcomes. Through reduced oxygen in the mother's blood and reduced oxygen delivery to the placenta, CO offers a plausible mechanism for an impact of biomass pollution on different perinatal health outcomes. Moreover, CO is cleared more slowly from fetal blood than from maternal blood due to the greater CO affinity of fetal hemoglobin.

Ischemic heart disease is a major cause of death in developing and industrialized societies alike. Epidemiological studies have linked cardiovascular disease to ambient air pollution, active smoking, and environmental tobacco smoke. As part of the RESPIRE randomized-controlled trial of an improved *plancha* stove undertaken in the highlands of Western Guatemala, a between-group and before-and-after comparison of blood pressure among women above 38 years of age was conducted. After comprehensively adjusting for confounders, the systolic and diastolic blood pressures of women living in homes with a chimney stove was, respectively, 3.7 mm Hg (95% confidence interval: -8.1; 0.6) and 3.0 mm Hg (95% confidence interval: -5.7; -0.4) lower than that of women living in homes with a traditional open fire. Daily average $PM_{2.5}$ exposures were 264 and $102 \mu\text{g m}^{-3}$ in the control and intervention groups, respectively.

ALRI, COPD, and Lung Cancer

Approximately 25 observational studies (predominantly using case-control designs) have investigated the link between indoor air pollution and childhood ALRI in developing countries. Only two of these studies were prospective cohorts and measured concentrations of pollutants. The other studies relied on proxy measures, such as cooking fuel type, time spent near the fire, or the child being carried on the mother's back. A first meta-analysis based on eight studies conducted in the Gambia, Nepal, Nigeria, Zimbabwe, and among Navajo Indians in North America yielded a relative risk of 2.3 (1.9; 2.7) for ALRI among children exposed to cooking with solid fuels. A more recent meta-analysis based on 24 studies resulted in an overall pooled odds ratio of 1.78 (1.45; 2.18). Despite substantial heterogeneity between studies and some evidence of publication bias, the odds ratios remained relatively stable in a series of sensitivity analyses.

Table 1 Status of evidence linking household combustion of biomass fuels and coal with child and adult health outcomes

Health outcome	*Age*	*Status of evidence*
Sufficient evidence for burden-of-disease calculation		
Acute lower respiratory infections	Child <five years	*Strong* Some 15–20 observational studies for each condition, from developing countries. Evidence is consistent (significantly elevated risk in most though not all studies); the effects are sizable, plausible, and supported by evidence from outdoor air pollution and smoking.
Chronic obstructive pulmonary disease	Adult women	
Lung cancer (coal exposure)	Adult women	
Chronic obstructive pulmonary disease	Adult men	*Moderate-I* Smaller number of studies, but consistent and plausible.
Lung cancer (coal exposure)	Adult men	
Not yet sufficient evidence for burden-of-disease calculation		
Lung cancer (biomass exposure)	Adult women	*Moderate-II* Small number of studies, not all consistent (especially for asthma, which may reflect variations in definitions and condition by age), but supported by studies of outdoor air pollution, smoking, and laboratory animals.
Tuberculosis	Adult	
Asthma	Child and adult	
Cataracts	Adult	
Adverse pregnancy outcomes	Perinatal	*Tentative* Adverse pregnancy outcomes include low birth weight and increased perinatal mortality. One or a few studies at most for each of these conditions, not all consistent, but some support from outdoor air pollution and passive smoking studies.
Cancer of upper aerodigestive tract	Adult	
Interstitial lung disease	Adult	
Ischemic heart disease	Adult	Several studies from developed countries have shown increased risk for exposure to outdoor air pollution at much lower levels than IAP levels seen in developing countries. No developing country studies yet.

Notes: Strong evidence: Many studies of solid fuel use in developing countries, supported by evidence from studies of active and passive smoking, urban air pollution, and biochemical or laboratory studies; moderate evidence: At least three studies of solid fuel use in developing countries, supported by evidence from studies on active smoking and on animals (Moderate I: strong evidence for specific age/sex groups. Moderate II: limited evidence).

A number of studies have examined chronic respiratory symptoms in women cooking with biomass fuels. Eight studies conducted in six countries – Bolivia, Colombia, India, Mexico, Nepal, and Saudi Arabia – quantified the association between indoor air pollution and COPD and were included in a recent meta-analysis. The relative risk for COPD in women over 30 years of age was found to be 3.2 (2.3; 4.8); in men over 30 years of age, it was estimated to be 1.8 (1.0; 3.2). Globally, tobacco smoking is considered to be the most important risk factor for COPD, but indoor air pollution from solid fuel use is likely to play a significant role among the large population of nonsmoking women in developing countries.

The vast majority of the internationally published studies on lung cancer and indoor air pollution were conducted in different provinces of China. Based on a meta-analysis of 16 case-control studies – 14 from China, 1 from Japan, and 1 from the USA – the relative risk of lung cancer from exposure to coal smoke in women over 30 years of age is 1.9 (1.1; 3.5); in men it is estimated to be 1.5 (1.0; 2.5). Owing to the paucity of studies, coal smoke exposure among men was classified as moderate-I evidence, but the findings of five studies including women and men combined add confidence to the interpretation of the observed effect as meaningful (Table 1).

The evidence for the impact of exposure to indoor air pollution on various health outcomes is almost exclusively based on observational studies of varying quality, which may be subject to serious limitations. In particular, as mentioned earlier in text, almost all studies relied on a relatively imprecise exposure measure, such as main type of cooking fuel, which is likely to inflate random error. Where a long lag time exists between exposure and disease, most studies make an implicit assumption about the stability of cooking practices over time, which – depending on the setting – may result in systematic error. Both types of error are, however, likely to bias the impact of indoor air pollution on health toward the null. In addition, the cleaner fuel comparison group in most studies is exposed to pollutant concentrations that exceed WHO air quality guideline limits. As a result, the potential health gains from removing exposure are likely to be an underestimate. In contrast, inadequate adjustment for confounding will overestimate the true strength of the relationship between exposure and health outcome. Many studies did not adjust for all other important risk factors, such as tobacco smoking and exposure to environmental tobacco smoke or outdoor air pollution in relation to COPD and malnutrition in relation to ALRI. In view of the close link between reliance on solid fuels and poverty, there may also be substantial residual confounding in the estimates. The need to rely almost exclusively on observational studies is, however, typical for research on environmental pollutants and does not per se prevent reaching robust public health conclusions. Nevertheless, care must be taken to minimize biases, exposure error, and confounding, as summarized in the section 'Conclusions and recommendations for research.'

Exposure–Response Relationship

Knowledge about the exposure–response relationship for different health outcomes remains sparse. Two studies to date have provided important insights into the characterization of the exposure–response relationship for the link between indoor air pollution and ALRI. A cohort study monitored 93 infants living in 55 randomly selected households in Kenya for more than two years. Exposure was assessed through continuous real-time monitoring of PM_{10} and CO combined with time-activity budgets; ALRI was assessed through weekly clinical examinations. ALRI rates increased at a higher rate for PM_{10} levels below $2000\,\mu g\,m^{-3}$ than for PM_{10} levels above $2000\,\mu g\,m^{-3}$, suggesting that the exposure–response relationship is not linear but levels off at concentrations of approximately $2000\,\mu g\,m^{-3}$. The other, a randomized-controlled trial in the highlands of Guatemala, conducted repeated 48 h kitchen, bedroom, and personal sampling of PM_{10} and CO for more than 500 children over an 18-month period. For a 50% reduction in personal exposure to CO, the RESPIRE trial found statistically significant reductions of approximately 25% in physician-defined pneumonia and approximately 33% in severe, hypoxemic pneumonia.

Burden of Disease Attributable to Indoor Air Pollution

Methodology

The WHO's comparative risk assessment utilized a population-attributable risk approach for disease burden calculations. In principle, this requires three kinds of information: (1) the distribution of exposure in the population, (2) the exposure–response relationship for each health outcome of interest, and (3) estimates of the background morbidity and mortality for each health outcome of interest, available from the Global Burden of Disease database.

In the absence of pollutant concentrations or personal exposure data, a binary exposure classification was adopted for the burden calculations for indoor air pollution by estimating the percentage of the population cooking with solid fuels *versus* nonsolid fuels (i.e., kerosene, gas, and electricity), as first used for a study of the national burden of disease in India. This allows linkage to the exposure metrics used in available epidemiological studies. In addition, to account for differences in cooking and ventilation practices, a ventilation factor was assigned to countries, depending on climate and the level of economic development. The method thus determines the burden caused by the pollution due to solid fuel use over the burden caused by the pollution from nonsolid fuels; it is not the total risk of indoor air pollution from all fuels.

As discussed in section 'Levels of evidence for different health outcomes,' the published evidence for the impact of indoor air pollution exposure on three health outcomes, that is, ALRI, COPD, and lung cancer in relation to coal use, was deemed sufficient for inclusion in the burden of disease calculations. Studies for these health outcomes had to be primary studies (not reviews or reanalyses) written or abstracted in English (and for lung cancer, Chinese) in peer-reviewed journals that reported an odds ratio and variance (or sufficient data to estimate them), and provided some proxy for exposure to indoor air pollution from the use of solid fuels for cooking and heating purposes.

Global, Regional, and National Burden of Disease

The burden of disease attributable to indoor air pollution was quantified at global and regional levels for the year 2000. Exposure estimates and the burden of disease from ALRI, COPD, and lung cancer were combined for each of the 14 WHO epidemiological subregions, as well as relative risks obtained through the above-mentioned meta-analyses. This yielded 1.6 million premature deaths and over 38.5 million DALYs attributable to solid fuel use globally for the year 2000. Globally, solid fuel use was estimated to be responsible for 910 000 ALRI deaths among children under five, 693 000 COPD deaths, and 16 000 lung cancer deaths. Children living in sub-Saharan Africa and South Asia are most affected by exposure to indoor air pollution; the greatest burden of COPD and lung cancer deaths is experienced by women living in South Asia and the Western Pacific region (China). In developing countries with high child and adult mortality, indoor air pollution was responsible for 3.7% of the burden of disease in 2000, making it the fourth most important risk factor. Worldwide, 2.6% of the total burden was attributable to indoor air pollution, making it second among all environmental health risk factors behind unsafe water, sanitation, and hygiene. More recently, based on the same methodology, country-by-country estimates of morbidity and mortality attributable to indoor air pollution from solid fuel use have also become available, but disaggregating large-scale modeling results for individual countries introduces much uncertainty. The Global Burden of Disease Project 2005 will provide updated estimates of the contribution of household solid fuel use and various other environmental risk factors to the burden of disease globally and in 21 epidemiological subregions.

Broader Health and Socioeconomic Impacts of Solid Fuel Use

Household air pollution is probably the most severe direct health risk associated with traditional household energy practices. Yet cooking and heating with solid fuels also impacts health and socioeconomic development in a variety of other ways. Being locked into traditional cooking practices may therefore represent a critical barrier for individuals, communities, and countries to escape from poverty. Indeed, the International Energy Agency, the United Nations Millennium Project, and the United Nations Development Programme all consider access to modern cooking fuels a requirement for economic and social development.

Burns, Unintentional Injuries, and Assaults

Children are at risk of burns and scalds, resulting from falling into open fires and knocking over pots of hot liquid. Data obtained as part of the RESPIRE randomized-controlled trial in Guatemala suggest a baseline burn rate of 41 per 1000 child years among children aged under 16 years (i.e., among the older siblings of the youngest child in the household). During follow-up, the rate of burns/scalds in the open fire group was recorded at 35 per 1000 child years, whereas the group receiving a *plancha* stove had an estimated rate of 18 per 1000 child years. In addition, the severity of the burns appeared to be substantially reduced in the intervention group. Even modern fuels, however, are not always safe, as children may be at risk from drinking kerosene, which is often stored in soft drink bottles.

Anecdotal evidence suggests that the collection of biomass fuels may increase the risk of various unintentional injuries, including snake bites, and backache, in particular among women and children. Carrying heavy loads may bring about prolapse during pregnancy. Reports from war zones and refugee camps provide testimony of girls and women being assaulted when they leave the relative safety of their homes to collect fuel or water.

However, there has been concern that efforts to reduce indoor air pollution could increase the risk of vector-borne disease, in particular malaria. A recent review of the limited literature on the repellent effect of smoke on mosquitoes found no conclusive evidence that smoke from domestic fuel use provides effective protection against malaria. It also suggests that the majority of malaria transmission in sub-Saharan Africa, even though it occurs indoors, takes place at night when smoke production is expected to be minimal.

Time and Household Expenditure

Where fuel is purchased, for example, in urban slums in Africa and Asia, spending money on inefficient fuels can place severe constraints on household budgets. Where fuel is collected, women and children may lose many hours a week searching for wood branches and twigs. Fuel collection is not necessarily a daily task, as the duration and frequency of collection vary depending on the availability of different fuels. In rural India, for example, daily fuel collection time ranges from only 20 min per day in Andhra Pradesh to more than 1 h per day in Rajasthan, which is mostly covered by desert. These substantial investments are aggravated by other household chores, such as cooking on inefficient stoves and cleaning soot-laden pots. Less time spent on fuel collection and cooking has the potential to free women's and children's time for other activities, such as child care or income-generating tasks and education, respectively.

Good health is crucial as household livelihoods rely on the health of family members. In addition to its direct effect on health, indoor air pollution exerts an indirect effect on the socioeconomic situation of the household: being ill or having to care for sick children leads to additional expenses for health care and medication while diminishing the time spent on formal or informal income generation.

Environmental Impacts

Solid fuel use can have a number of important environmental consequences. Household use of solid fuels in high-density rural and urban environments contributes to outdoor air pollution. For example, a Bangladeshi study conducted in a semi-residential area of Dhaka and in an urban area of Rajshahi identified soil dust, road dust, cement, sea salt, motor vehicles, and biomass burning as major sources of airborne PM; household combustion of biomass contributed approximately half of the mass in $PM_{2.5}$ samples from Rajshahi.

Approximately 2.4 billion people rely on wood and charcoal to boil water and to cook food, resulting in an estimated 2 million tonnes of biomass burnt on a daily basis. Combined with population pressure, poor forest management, and clearance of land for agriculture and building timber, the use of wood as fuel can contribute to local deforestation, especially where households resort to the use of freshly cut (green) wood, which is also more polluting and less efficient. During the 1990s, forest plantations rendered unproductive due to illegal cutting of wood for fuel were a common sight in China and provided the main motivation for the establishment of the Chinese National Improved Stoves Programme.

Charcoal is a popular fuel among many low-income urban populations because of its relative cleanliness, safety, and affordability, and its use is particularly widespread in sub-Saharan Africa, even in countries with substantial fossil fuel resources such as Nigeria. Currently, charcoal in sub-Saharan Africa is predominantly produced in traditional kilns with suboptimal conversion efficiency and no conversion controls. Combined with the unsustainable harvesting of fuels, this can place severe stress on forests and have important, although poorly characterized, impacts on soil fertility and biodiversity. In addition, both the production and the inefficient household use of charcoal result in substantial greenhouse gas emissions.

The burning of biomass fuels in poor homes in the developing world does not convert all fuel carbon into carbon dioxide (CO_2) and water. Products of incomplete combustion include the potent greenhouse gas methane (CH_4), which has a markedly higher global-warming potential than CO_2. When the combined emissions of CO_2 and other greenhouse gases are considered for the same amount of energy delivered, wood, crop residues, and dung burnt in traditional poor-combustion stoves release more greenhouse gas emissions than fossil fuels, such as kerosene and LPG. This holds true even where biomass fuels are renewably harvested. Notably, to deliver the same amount of energy, dung used in a biogas digestor produces only 1% of the greenhouse gas emissions of those produced by dung burnt in a traditional stove.

As the use of biomass fuels and coal for cooking and heating accounts for more than 10% of human energy use, it is increasingly being argued that more efficient and cleaner household energy systems in developing countries could provide a significant double benefit in the form of reduced greenhouse gas emissions (with opportunities for carbon trading via the Clean Development Mechanism) and improved health through reduced indoor air pollution.

Conclusions and Recommendations for Research

Exposure to indoor air pollution has substantial and serious consequences for the health of the 3 billion people who continue to rely on solid fuels to meet most of their basic energy needs. A majority of the estimated 1.6 million annual premature deaths attributable to this risk factor occur among children under five years of age and women; high-mortality developing countries in Africa and South Asia are disproportionately affected. In addition, traditional household energy practices can put a substantial burden on household expenditure, absorb time that might otherwise be used toward income generation, and negatively impact the local and global environment. Therefore, interventions aiming to reduce indoor air pollution must be devised and implemented in the context of overall development and poverty eradication.

Although indoor air pollution from solid fuel use is now considered an established risk factor for ALRI, COPD, and lung cancer (in relation to coal use), little is known about the exposure–response relationship for these and other health outcomes. In particular, research should strive to elucidate the links between household combustion of solid fuels and those other health outcomes that make a substantial contribution to the overall burden of disease, such as perinatal health outcomes, tuberculosis, and cardiovascular disease. Use of the most suitable study designs, in particular well-conducted prospective cohort studies as well as efficacy and effectiveness trials of interventions, should be combined with reliable assessments of concentrations of and personal exposure to PM_{10}, $PM_{2.5}$, CO, and other important pollutants. In parallel, validating harmonized survey questions on cooking practices through measurement of ambient concentrations and personal exposure could improve our understanding of how factors, such as the use of multiple fuels, stove type and stove ventilation, cooking setting, and ventilation, generate different exposure profiles. Although most studies to date have focused on cooking, other household energy uses, such as space-heating, water boiling, or specific cultural practices, may also pose substantial health risks.

Ultimately, all of the above – more advanced data on cooking practices and more reliable information on the links between exposure and critical health outcomes – will be needed to refine assessment of the burden of disease from the household combustion of solid fuels at global, regional, and national levels. Knowledge of the magnitude of the public health problem, combined with information on the effectiveness and efficiency of technical solutions, is the evidence required to inform policies and programs toward the large-scale implementation of interventions to reduce indoor air pollution.

See also: Environmental Tobacco Smoke and Health Risk Assessment, Household Energy Solutions in Developing Countries.

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