Energy Systems and Population Health

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1 Introduction

It is well-documented that energy and energy systems have a central role in social and economic development and human welfare at all scales, from household and community to regional and national (41). Among its various welfare effects, energy is closely linked with people's health. Some of the effects of energy on health and welfare are direct. With abundant energy, more food or more frequent meals can be prepared; food can be refrigerated, increasing the types of food items that are consumed and reducing food contamination; water pumps can provide more water and eliminate the need for water storage leading to contamination or increased exposure to disease vectors such as mosquitoes or snails; water can be disinfected by boiling or using other technologies such as radiation. Other effects of energy on public health are mediated through more proximal determinants of health and disease. Abundant energy can lead to increased irrigation, agricultural productivity, and access to food and nutrition; access to energy can also increase small-scale income generation such as processing of agricultural commodities (e.g. producing refined oil from oil seeds, roasting coffee, drying and preserving fruits and meats) and production of crafts; ability to control lighting and heating allows education or economic activities to be shielded from daily or seasonal environmental constraints such as light, temperature, rainfall, or wind; time and other economic resources spent on collecting and/or transporting fuels can be used for other household needs if access to energy is facilitated; energy availability for transportation increases access to health and education facilities and allow increased economic activity by facilitating the transportation of goods and services to and from markets; energy for telecommunication technology (radio, television, telephone, or internet) provides increased access to information useful for health, education, or economic purposes; provision of energy to rural and urban health facilities allows increased delivery and coverage of various health services and interventions such as tests and treatments, better storage of medicine and vaccines, disinfection of medical equipment by boiling or radiation, and more frequent and efficient health system encounters through mobile clinics or longer working hours; and so on. In fact, while the dominant view of development-energy-health linkages has been that improvements in energy and health are *outcomes* of the socioeconomic development process (e.g. the "energy ladder" framework discussed below), it has even been argued that access to higher quality energy sources and technologies can *initiate* a chain of demographic, health, and development outcomes by changing the household structure and socioeconomic relationships. For example, in addition to increased opportunities for food and income production, reduced infant mortality – as a result of transition to cleaner fuels or increased coverage of vaccination with availability of refrigerators in rural clinics – may initiate a process of "demographic transition" to low-mortality and low-fertility populations (14). Such a transition has historically been followed with further improvements in maternal and child health and increased female participation in the labor markets and other economic activities.

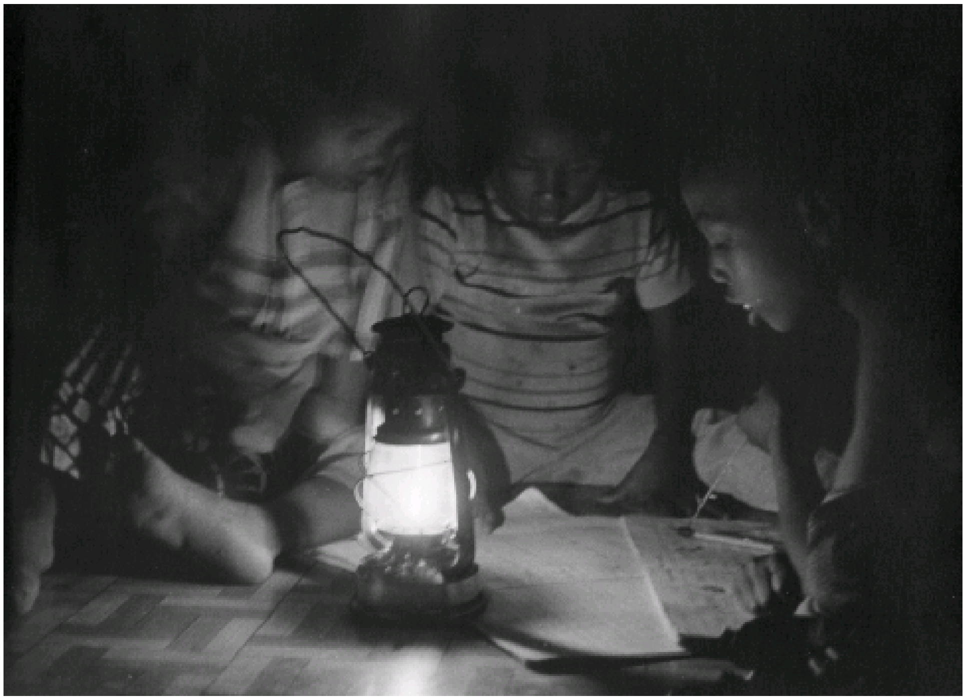


Figure 1: Energy is essential for many aspects of development such as education, with important public health implications (photograph by A. Feyami, Nigeria)

The effects of energy on population welfare and health are also closely related to the source of energy and type of conversion technology utilized (46). Harvesting energy from hydropower and biomass resources can affect the local environment through soil erosion, and disruption or modification of water system or soil nutrient cycle. This may lead to reduced agricultural productivity, limited access to water and energy, changes in local vegetation, and altered disease vector dynamics – all with important health consequences. Energy generation from combustion of biomass or fossil fuels, even using best currently-available technologies, results in release of a large number of pollutants that are known or potential hazards to human health and ecological systems. Fuel extraction and combustion both contribute to the stock of atmospheric greenhouse gases (GHGs) that lead to climate change, with potential health implications (88). Nuclear energy, which does not have combustion by-products, raises concerns about reactor safety as well as transport and storage of nuclear waste. Therefore, while energy has numerous benefits to social and economic development and public health, the process of energy production can result in short- and long-term effects on environmental determinant of health (41-44, 93, 105).

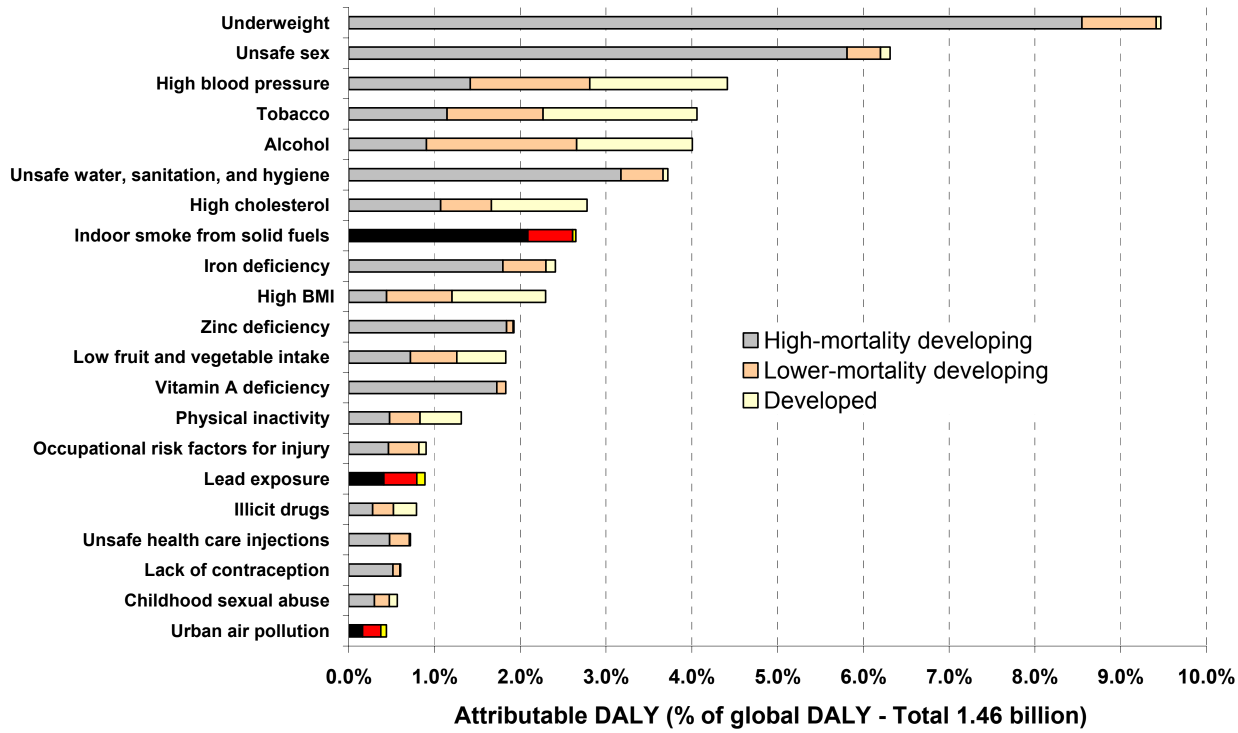


Figure 2: Burden of disease, measured in disability-adjusted life years (DALYs), for some of the direct effects of energy systems (highlighted in black, red, and yellow), relative to other major global risk factors (see (34, 125) for a description of methods). DALYs are an aggregate measure of loss of life to premature mortality and time lived with non-fatal health outcomes.

In this paper we review the current research on the implications of energy systems on public health, with emphasis on recent findings on linkages and routes that have global importance. Currently more than 60% of global energy consumption takes place in industrialized countries, with per capita consumption averaging five times that of developing countries (127). Contributions to GHG emissions follow a similar pattern. Per capita energy consumption in North America is more than 25 times the poorest nations in sub-Saharan Africa, 20 times per capita consumption in India, and 10 times China (127). Global carbon emissions are approximately one metric ton of carbon per year per person (tC/person-year). For example, per capita emissions in the United States are more than 5 tC/year compared to approximately 0.6 tC/year in developing countries as a whole, and less than 0.2 tC/year in the 50 lowest-emissions developing nations (8). The most rapid future growth in energy consumption is, however, expected to take place in developing countries, as a result of both demographic and economic changes (44, 92, 93). Further, the fuels and energy conversion technologies currently used in developing nations result in much higher local exposure to pollution (106). Therefore, from both socioeconomic and public health perspectives, energy options in developing countries are of notable importance. This paper, therefore, primarily focuses on developing countries, where much of negative health consequences arising from limited access to clean energy are concentrated. We emphasize that many aspects of energy use and its consequences are linked between developing and industrialized countries.

Although we describe energy as a source of pollution and disease in detail, we emphasize that energy is an instrument for development and for improving public health as described above. The challenge of sustainable development policy is therefore two-sided, to provide energy for human development and to minimize its negative effects. Throughout the paper, we also identify knowledge gaps that should motivate new data collection and research. The following section of the paper discusses energy-environment-health linkages, including ambient and indoor air pollution with emphasis on the linkages between household or local and global impacts including global climate change. Section 3 focuses on two social dimensions of energy and health linkages: poverty and gender. We then discuss some of the options for reducing “energy poverty” (92,

123) while minimizing the negative consequences of energy use, with emphasis on the importance of technological innovation and management.

2 The Environmental Health Implications of Energy and Energy Technology

2.1 Ambient air pollution

The burning of oil, coal, natural gas, and biomass emits complex mixtures of gases and particles, which spread in the atmosphere from the original emissions source. These combustion products can reduce visibility, produce acid rain which can damage plants and erode buildings and other objects, and cause or exasperate multiple disease over short and long time periods. Although urban biomass use is still significant in many regions of the world, globally urban air pollution is largely and increasingly the result of the combustion of fossil fuels for transport, electricity generation and domestic use (23, 56, 126). While it is likely that the health effects of ambient air pollution are a result of the complex mixture of combustion products, negative health effects have been most closely correlated with three species of pollutants in epidemiological studies: fine particulate matter, sulfur dioxide, and tropospheric ozone (23, 51). Toxic material such as lead and other metals, which are present in some fuels, also have significant health effects.

Fine particulate matter (PM – also known as aerosols) is produced as a primary product of combustion processes (such as diesel soot) as well as a "secondary species" when gases react to form particles (e.g. sulfate particles formed from the burning of sulfur-containing fuels such as coal). Aerosols are commonly placed in several categories, including black carbon, organic carbon, sulfates, nitrates, dust, and even sea salt. The composition of PM depends strongly on its source, and a single particle may contain a combination of species. Although the role of the chemical composition and physical characteristics of PM in disease causation and exasperation are subject of ongoing research, there is general agreement that particle size is a strong determinant in its health impact (91). The class of PM below 2.5 microns in aerodynamic diameter ($PM_{2.5}$) is the focus of much health-related inquiry, as these small particles can penetrate deep into the lung (23, 51, 101, 121).

The consequences of exposure to high levels of ambient air pollution were observed in the mid-20th century when cities in Europe and the United States experienced air pollution episodes, such as the 1952 London fog, that resulted in many excess deaths and hospital admissions. Subsequent clean air legislation, regulation, and technological advance have reduced ambient air pollution in many cities, especially in the higher-income countries.[1] However, recent epidemiological studies, using sensitive designs and analyses, have identified health effects of combustion-derived air pollution even at the low ambient concentrations typical of Western European and North American cities (50, 91). At the same time, the populations of the rapidly expanding mega-cities of Asia and Latin America are increasingly exposed to levels of ambient air pollution that rival and often exceed those experienced in industrialized countries in the first half of the 20th century (23, 69) (Figure 3 and Table 1).

[1] The relationship between economic development and air pollution in many societies has followed a pattern of initial increase in pollution followed by subsequent decline at higher income levels. This "inverted-U" relationship, referred to as an Environmental Kuznets Curve (EKC), has been used for policy formulation (122), although a number of methodological and conceptual questions have been raised about their validity and generalizability (37).

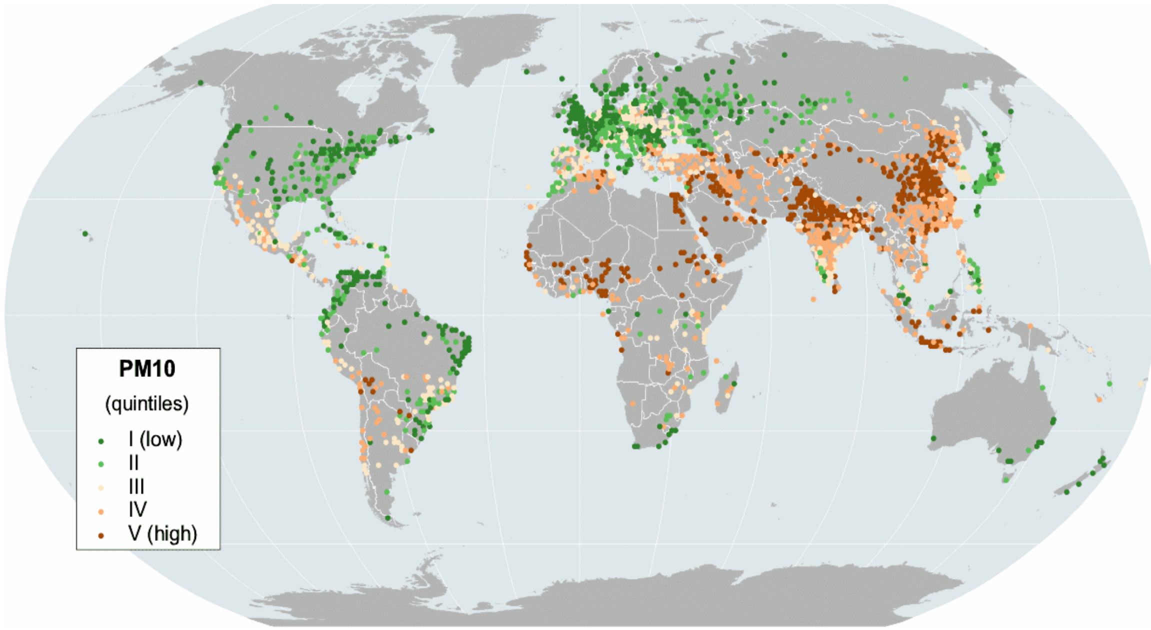


Figure 3: Estimated annual average concentrations of PM_{10} (particulates below 10 microns in aerodynamic diameter) in cities with populations of 100,000 or more and national capitals in 2000 (source: (23)).

Table 1: Exposure to ambient air pollution in various regions of the world. The indicator pollutant considered is PM_{10} (source: (23); see Figure 4 in (23) for the distribution of pollution levels in the cities in each region).

Region [a]	**Proportion of population in cities > 100,000 (%)**	**Mean urban PM_{10} concentration** ($\mu g/m^3$)
African region (D)	23	63
African region (E)	20	39
Region of the Americas (A)	71	25
Region of the Americas (B)	50	38
Region of the Americas (D)	41	51
Eastern Mediterranean Region (B)	41	40
Eastern Mediterranean Region (D)	29	83
European Region (A)	39	26
European Region (B)	37	48
European Region (C)	45	31
South-East Asia Region (B)	18	93
South-East Asia Region (D)	17	76
Western Pacific	65	32

Region (A)		
Western Pacific Region (B)	34	84

[a] The regions are the administrative regions of the World Health Organization's Global Burden of Disease (GBD) Project. See appendix for definition of regions and list of countries in each.

Although urban ambient air pollution has been commonly defined at the level of a city in most epidemiological studies (91), recent research has illustrated the variation of exposure to this risk and the associated health effects in considerably smaller microenvironments (50, 74, 75, 121). This variability occurs because: (i) the ambient concentrations, composition, and dispersion of pollutants depend on the characteristics and location of pollution source(s) (e.g. mobile or stationary, combustion fuel and technology, etc.), meteorological factors, and urban physical characteristics, (ii) indoor concentrations (e.g. in buildings and vehicles) as a result of ambient pollution depend on the locations, type, and structure of indoor environments, and (iii) individuals and groups spend various amounts of time in different indoor and outdoor urban microenvironments (87). For example, in a study of selected microenvironments in Boston, USA, it was found that PM_{10} concentrations varied more across selected indoor microenvironments where people regularly spend time (e.g. subways, buses, restaurants, etc.) than outdoor environments (74). A recent study of increased mortality associated with ambient air pollution in the Netherlands highlights the importance of accurate characterization of spatial distribution of exposure. The study found that cardiopulmonary mortality was more affected by long-term exposure to air pollution due to living near a major road than from exposure to larger-scale urban and regional air pollution (50).

Many of the epidemiological studies on the relationship between ambient air pollution and health have been conducted at relatively low concentrations observed in North American and European cities. In addition to difficulties in measuring or estimating exposure, quantifying health effects at high pollution levels in many developing country cities has required extrapolation of the concentration-response relationship beyond its observed range, with associated uncertainty. Estimates of global mortality as a result of exposure to ambient urban air pollution are provided in Table 2.

Table 2: Mortality and burden of disease as a result of exposure to ambient air pollution in 2000 (source: (34, 125)).

	Death in children under 5 years of age	**Adult deaths**	**Burden of diseases (thousands of DALYs)** [a]
High-mortality developing countries (38% of global population)	18,000	202,000	2,346
Lower-mortality developing countries (40% of global population)	7,000	419,000	3,095
Demographically and economically developed countries (22% of global population)	1,000	153,000	961

[a] Burden of disease is a measure of loss of healthy life due to premature mortality and morbidity. It is expressed in disability-adjusted life years (DALYs) (82). In the year 2000, there were a total of 1.46 billion DALYs lost in the world due to premature mortality and non-fatal health outcomes.

Important research themes which would allow more systematic use of technological and regulatory instruments for reducing the health consequences of ambient air pollution include:

- the role of particle composition and size distribution on the incidence or severity of various diseases;
- models and data to estimate the spatial distribution of pollution within individual cities or regions and its role on population exposure;
- the health effects of sustained exposure at high concentrations typical of many cities in developing countries;
- the interactions of ambient air pollution and other cardiopulmonary risk factors such as indoor air pollution, smoking, dietary factors, and occupational exposure.

2.2 Indoor air pollution [2]

Globally, almost three billion people rely on biomass (wood, charcoal, crop residues, and dung) and coal as their primary source of domestic energy (93, 126) (Figure 4 and Table 3). Biomass accounts for more than one half of domestic energy in many developing countries, and for as much as 95% in some lower income ones (7, 93).

[[[Figure to be inserted upon receipt in required form from authors]]]

Figure 4: National household solid-fuel use estimates in 2000 (source: (112)).

Table 3: Prevalence of solid fuel use in different in various regions of the world. In some regions (such as the European region) with better ventilation, exposure levels among solid fuel users are lower (source: (110)).

Region [a]	**Household solid fuel use (% all households)**
African region (D)	73
African region (E)	86
Region of the Americas (A)	2
Region of the Americas (B)	25
Region of the Americas (D)	53
Eastern Mediterranean Region (B)	6
Eastern Mediterranean Region (D)	55
European Region (A)	0
European Region (B)	42
European Region (C)	23
South-East Asia Region (B)	67
South-East Asia Region (D)	84
Western Pacific Region (A)	0
Western Pacific Region (B)	78

[2] See also (32, 33).

[a] The regions are the administrative regions of the World Health Organization's Global Burden of Disease (GBD) Project. See appendix for definition of regions and list of countries in each.

When solid fuels like biomass or coal are burned, hundreds of harmful chemical substances are emitted in the form of gases, liquids (suspended droplets) or solids (suspended particulates). These emissions occur in particularly large quantities when such fuels are burned in devices characteristic of developing country households, which are often open hearths or poorly ventilated stoves. The pollutants released include carbon monoxide, nitrogen dioxide (NO_2), particles in the respirable range (<10 μm in aerodynamic diameter), and other organic matter (predominantly composed of polycyclic aromatic hydrocarbons such as benzo[a]pyrene and other volatile organic compounds such as benzene and formaldehyde) (25, 105, 128). Combustion of coal in addition to the above pollutants may release oxides of sulfur, and heavy metal contaminants including arsenic and fluorine (39). Monitoring of pollution and personal exposures in biomass-burning households has shown concentrations many times higher than those in industrialized countries. The latest National Ambient Air Quality Standards of the US Environmental Protection Agency, for instance, required the daily average concentration of PM_{10} to be below 150 $\mu g/m^3$ (annual average below 50 $\mu g/m^3$). In contrast, typical 24-hour average concentration of PM_{10} in homes using biofuels may range from 200 to 5,000 $\mu g/m^3$ or more throughout the year, depending on the type of fuel, stove, and housing (35, 58, 105, 106, 108, 113). Overall, it has been estimated that approximately 80% of total global population exposure to air-borne particulate matter occurs indoors in developing nations (106, 108).

Exposure to indoor air pollution (IAP) from the combustion of solid fuels has been implicated, with varying degrees of evidence, as a causal agent of several diseases in developing countries including acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), lung cancer (for coal smoke), asthma, nasopharyngeal and laryngeal cancer, tuberculosis, low birth weight, and diseases of the eye such as cataract and blindness (16, 20, 30, 113). Most current epidemiological studies on the health impacts of exposure to indoor air pollution (IAP) in developing countries have focused on the first three of the above diseases (20, 113). Estimates of global mortality from exposure to indoor solid fuel smoke are shown in Table 4.

Table 4: Mortality and burden of disease as a result of exposure to indoor air pollution from solid fuels in 2000 (source: (34, 125)) for ARI, COPD, and lung cancer.

	Death in children under 5 years of age	**Adult deaths**	**Burden of diseases (thousands of DALYs) [a]**
High-mortality developing countries (38% of global population)	808,000	232,000	30,392
Lower-mortality developing countries (40% of global population)	89,000	468,000	7,595
Demographically and economically developed countries (22% of global population)	13,000	9,000	550

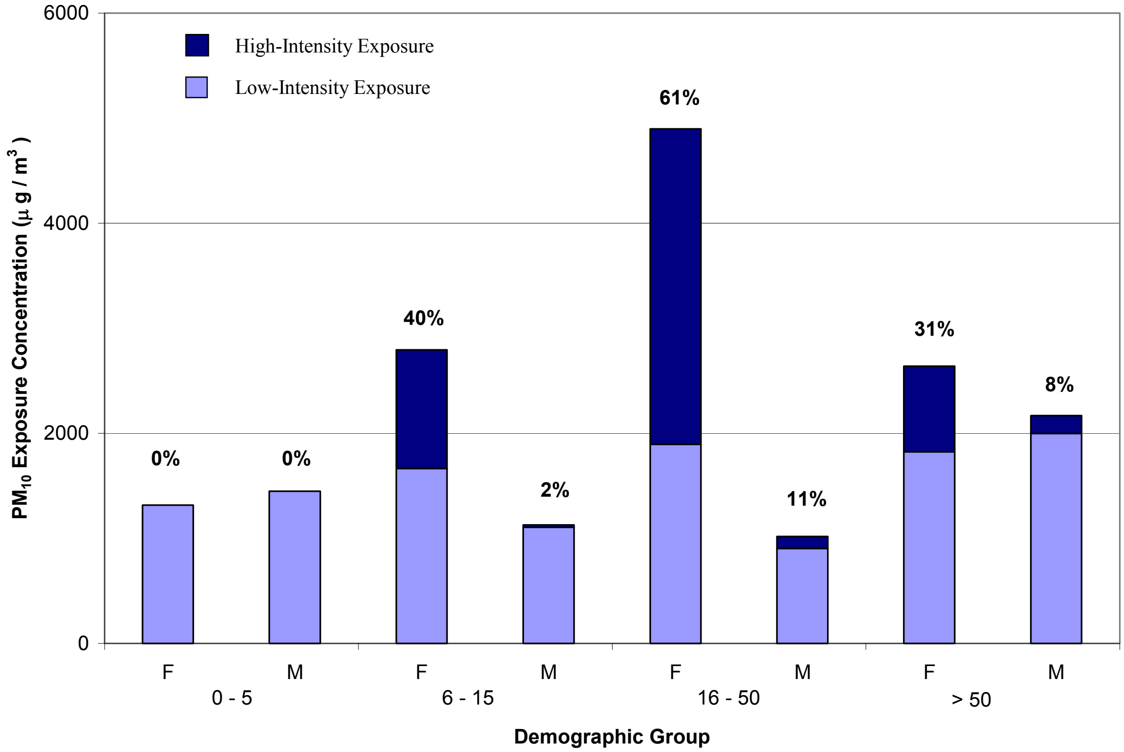
While detailed epidemiological and toxicological studies on the health effects of exposure to indoor air smoke from solid fuels are recent phenomena, and a number of important questions remain, there is increasing consensus of its important role in the burden of disease, especially among the poor and marginalized parts of many societies (20, 111). As a result, the attention of the research community has shifted to the knowledge required for design and dissemination of interventions (32, 33, 120). Reducing exposure to indoor air pollution from solid fuels can be achieved through modifications in fuel type and energy conversion technology, housing and ventilation, and behavioral factors such as fuel preparation and individual time-activity budgets (32, 120). To date, most research has focused on the first method, with emphasis on improved stoves and fuels, which are believed to provide more affordable options in the near term than a complete shift to non-solid fuels. Initial improved stove research and development efforts, however, were often marked by a lack of detailed data on stove performance. Efficiencies and emissions, for example, were often measured in controlled environments with technical experts using the stoves under conditions very dissimilar to those in the field (68, 77).[3]

Recent analysis of multiple determinants of exposure including continuous data on pollutant concentrations throughout the day, spatial dispersion of smoke inside the house, and quantitative and qualitative data on time-activity budgets of individual household members, as well as other routes of exposure, have shown a complex environmental-behavioral exposure mechanism (32). For example, emissions from open biomass stoves vary greatly over short time intervals, with the peaks in emissions commonly occurring when fuel is added or moved, the stove is lit, the cooking pot is placed on or removed from the fire, or food is stirred (35, 36) (Figure 5A). Because household members who cook are closest to the stove at such times, peak emissions are important contributors to the exposure of female household members (Figure 5B) (36). As a result, people who cook gain disproportionately small benefits from increased housing ventilation compared to those who are further away from the stove (10, 31). Implementing programs that promote cleaner fuels or designing stove technologies that reduce (peak) emissions, on the other hand, would provide comparably larger benefits to female household members (31). The mechanism of exposure to trace elements (e.g. arsenic and fluorine) is however different in some coal burning provinces of China, where drying food over the stove for long durations results in bioaccumulation of these pollutants in food (Figure 6) (39). In such

[3] The initial emphasis of research on household energy in developing countries was on environmental impacts of biomass use, such as impacts on deforestation and desertification, resulting in a level of zeal for increased efficiency with expert perspectives often disconnected from the local perceptions of fuel scarcity and improved efficiency (2, 58, 59, 63, 68, 77). The public health benefits from reduction in exposure to indoor smoke as well as the reduction in carbon emissions became the subject of attention soon after. This “double-dividend” – improving public health while reducing adverse environmental impacts – focused a great deal of effort on the design and dissemination of improved stoves (11, 59, 114).

cases, alternative food drying techniques and behavioral change by washing food before consumption can reduce exposure and associated health effects, such as arsenic poisoning and dental or skeletal fluorosis. Whether energy is used for heating is also a crucial determinant of exposure because heating, by definition, involves longer hours of energy use and closer distance of people to the location of combustion.

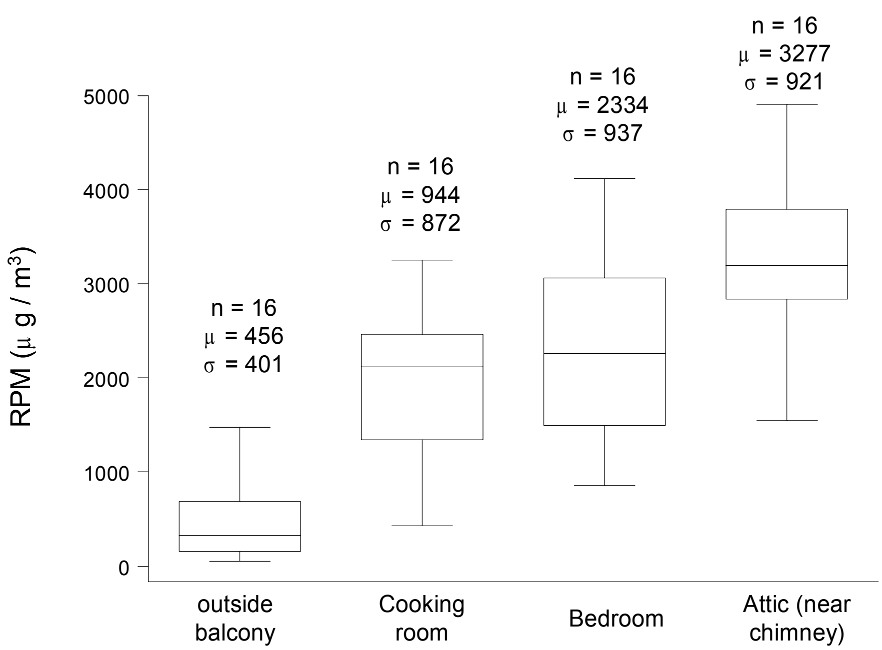
(a)



(b)

Figure 5: (a) In central Kenya, household members who cook are exposed to episodes of high pollution level when they work directly above the fire. (b) For each demographic group the total height of the column is the group average exposure concentration divided into average for high- (darker shade) and low-intensity (lighter shade) components. The percentages indicate the share of total exposure from high-intensity exposure. The high-intensity component of exposure occurs in less than one hour, emphasizing the intensity of exposure in these episodes. (Figure from (36)).

(a)



RPM (μ g / m³)
5000
4000
3000
2000
1000
0
n = 16
μ = 456
σ = 401
n = 16
μ = 944
σ = 872
n = 16
μ = 2334
σ = 937
n = 16
μ = 3277
σ = 921
outside balcony
Cooking room
Bedroom
Attic (near chimney)

(b)

Figure 6: An important route of exposure to fluorine and arsenic from stove use in southern China is bioaccumulation in food (corn and chili) (a) which are dried near a chimney where pollution levels are highest (b).

Beyond technical performance, some of the issues surrounding the success of intervention programs after community implementation (versus technology performance) have been discussed using a limited number of available case studies in various countries (1, 11, 53, 61, 77, 114, 120). Some important areas for future research include:

- The relative contributions of energy technology (stove-fuel combination), housing characteristics (such as the size and material of the house, the number of windows, and arrangement of room), and behavioral factors (such as the amount of time spent indoors or near the cooking area), including multi-stove and multi-fuel scenarios, to exposure;
- identifying the relative contributions of cooking and heating to exposure, including in different seasons;
- the exposure – response relationship for various diseases in order to estimate the health benefits of partial exposure reduction;
- longitudinal monitoring of both technical performance and adoption of interventions, as well as their economic and institutional determinants.

2.3 Local-global linkages [4]

Greenhouse gases (GHGs) and pollutants that affect health arise from similar processes of incomplete combustion, creating tight linkages among the multiple environmental and health

[4] The ecological effects of energy supply, including change in soil and vegetation dynamics as a result of biomass harvesting, construction of dams, or pollution are also important effects of energy use, not reviewed in this paper given its central focus on population health.

impacts of energy use.[5] Air pollution transport on regional to intercontinental scales is emerging as an important component of air quality and health (6). Sophisticated atmospheric models allow estimating the flow of pollution between different countries or regions (57, 116), and satellite, aircraft, and ground-based measurement systems have tracked plumes of particles and gases moving across the Pacific and Atlantic. Figure 7 presents model estimates of ozone dispersal from North America, Europe, and Asia (76) illustrating the extent of regional impacts even for a single pollutant.

[5] Global climate change and the associated shifts in both the mean and variance of meteorological variables such as temperature and precipitation will undoubtedly affect population health in many societies and geographical areas (88). Treating climate change as a "risk factor" in the same way as ambient and indoor air pollution described above, however, masks the complex socioeconomic, physical, and ecological determinants of health that mediate and modulate the climate-health relationship, especially as these other factors also change over long time scales due to economic and demographic development and technological innovation (21, 48, 94, 95).

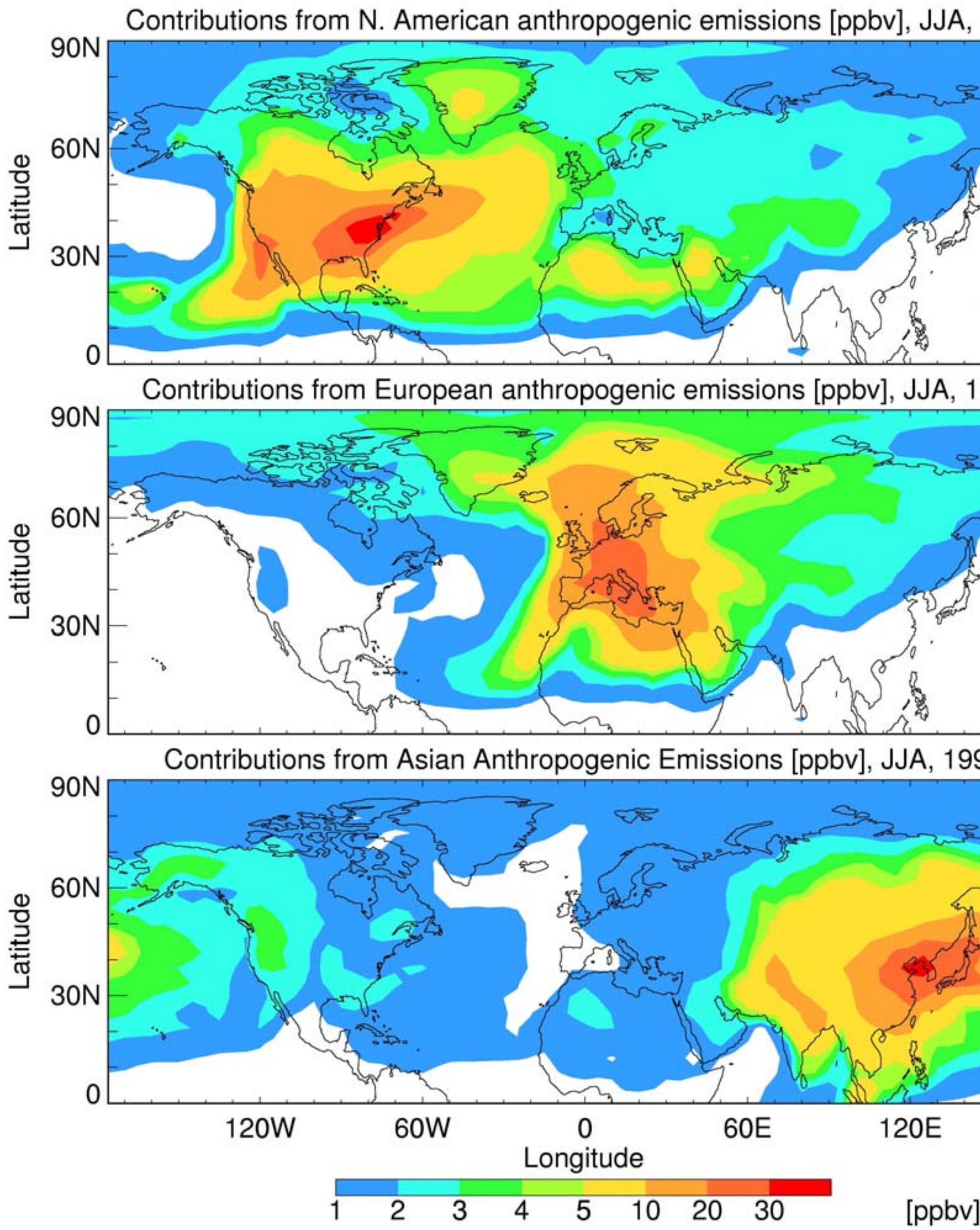


Figure 7: Model estimates of ozone from North America, Europe, and Asia during summer, 1997 (source: (76))

A number of works have also considered environmental effects, including GHG emissions, from household energy use in developing countries (9, 17, 47, 52, 65, 71, 115). Under optimal conditions, combustion of biomass, which is essentially a hydrocarbon fuel with a few trace elements, results almost entirely in the emission of water vapor and carbon dioxide (CO_2). As a result, if biomass is harvested in a sustainable way so that long-term stocks of biomass are not depleted, and burned under ideal combustion conditions, it is effectively GHG neutral.[6] We can therefore identify two critical factors that affect the extent of GHG emissions from biomass energy production: the sustainability of the biomass harvest and the nature of biomass combustion.

The issue of sustainable biomass harvesting is important, both from the perspective of carbon stocks and flows, and more importantly from the perspective of household welfare in developing countries and has been discussed elsewhere (2, 47, 65, 71, 84). Under conditions of incomplete combustion typical of most household level technologies in developing countries, hundreds of gaseous and aerosolized compounds are emitted in addition to CO_2 and water vapor (41, 105). Though CO_2 is the most commonly discussed greenhouse gas, particularly in fossil fuel-based systems, it is the non-CO_2 greenhouse gases that are more relevant in assessing GHG emissions from biomass combustion. This is because under a system of sustainable fuel use, CO_2 released by combustion is removed from the atmosphere by future plant growth. However non-CO_2 GHGs are not absorbed by photosynthesis and remain in the atmosphere despite new biomass growth (73). These non-CO2 GHGs, such as methane (CH_4) have a greater warming effect than CO2 on a molar basis (55).

[6] This is not the case for coal which is a fossil fuel with extensive GHG implications, because its stock cannot be replaced in the same way as biomass.

Total emissions of GHGs for a number of developing-country household energy technologies (stove-fuel combinations) using measurements or estimates of various pollutants (CO_2, methane, CO and non-methane hydrocarbon, NMHCs) have been calculated and are presented in Figure 8. The height of each bar shows the average emissions of each pollutant per unit energy in the fuel, while the lines show the sum of non-CO_2 GHGs (squares) and all GHGs, including CO_2 (circles). For biomass fuels, the former represents fuels that are harvested in a sustainable bioenergy cycle, so that biomass stocks are not depleted over time and CO_2 may be omitted from the calculation of net global warming effect, while the latter is applicable if stocks of biomass are fully depleted. Because fossil fuels do not allow for CO_2 replacement, the accounting of GHGs must always include CO_2 and the non-CO_2 line is omitted for these fuels. Note that both LPG and kerosene have energy-based emissions that are comparable to, if not lower than, the emissions from renewable biofuels, and are far lower than the emissions from biofuels when they are not used renewably. This result implies that, given current combustion technology and behavior, a shift to kerosene and LPG can reduce exposure to indoor air pollution without additional GHG emissions (109).[7]

[7] To use kerosene and LPG as an intervention for reducing the health hazards of indoor air pollution with high coverage would necessitate considerably larger supplies than currently accessible by most developing countries and infrastructure for its delivery (see also Table 5).

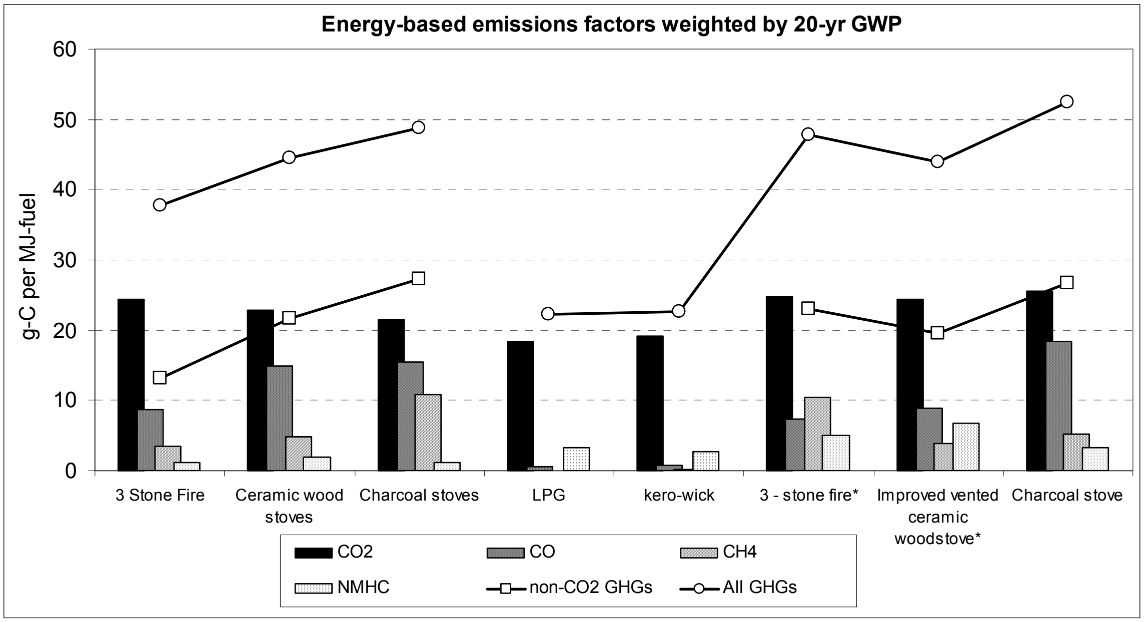


Figure 8: Comparison of energy-based emission factors by stove-fuel category for India and Kenya. The left 3 stoves are estimates from Kenya (source: (9)) and the right 5 from India (source: (115)). All biomass stoves used Acacia wood or charcoal made from Acacia during measurements.

The linkages between exposure to pollution at various scales and global environmental impacts may provide an opportunity to simultaneously address multiple energy-environment-health issues (45) (Text Box 1). At the same time, given the lower historical and current per-capita emissions of greenhouse gases in developing countries and the prominence of diseases that are affected by poverty and lack of access to clean energy and water, any attempt to reduce global environmental impacts should not jeopardize welfare gains in these countries (107). Further, the complexities of energy-development-environment-health linkages may at times require more integrated policy analysis (including joint implementation of multiple policies), rather than a simple "double-dividend" approach (Text Box 2).

Insert Text Box 1 Here

Insert Text Box 2 Here

3 Social Dimensions of Energy-Health Linkages [8]

3.1 Energy, poverty, and health

While the poor in industrialized nations spend a larger fraction of household budget on energy, the poverty-energy links are strongest in developing countries. It is well-known that the poor households in developing countries have limited access to clean and secure sources of energy, due to lack of resources and infrastructure (123). In a participatory poverty assessment in South Africa, which aimed to provide an understanding of poverty from the perspective of those who experience it, lack of access to clean energy and energy insecurity were identified as indicators of poverty and ill-being by the poor themselves (80).

Figure 9 shows the fraction of households using solid fuels among those living on less than 1 dollar per day, between 1 and 2 dollars, and greater than 2 dollars per day in various regions. As seen, except in sub-Saharan Africa, where solid fuels are by far the dominant source of domestic energy and common among all socioeconomic groups, the poor are considerably more likely to depend on more polluting fuel sources (if considered across, rather than within, regions, the higher solid fuel use in sub-Saharan Africa would strengthen the poverty-fuel correlation because incomes are generally lower in sub-Saharan Africa than other regions). The poor are also likely to live in parts of cities which are more affected by urban ambient air pollution such as near highways and industrial sites (85, 90, 102, 103). For example, a review of lead poisoning in China found that those children residing in industrial and busy traffic areas had average blood lead levels (BPb) of 21.8-67.9 μg/dl (104). The percentages of BPb values above 10 μg/dl, (which is the definition of lead poisoning in children), ranged from 64.9% to 99.5%. High exposure to pollution as a result of restricted access to clean energy, coupled with increased susceptibility from simultaneous exposure to malnutrition, poor water and sanitation, and other risk factors, means that the health impacts of energy are often disproportionately greater on the poor than those in other income strata (38).

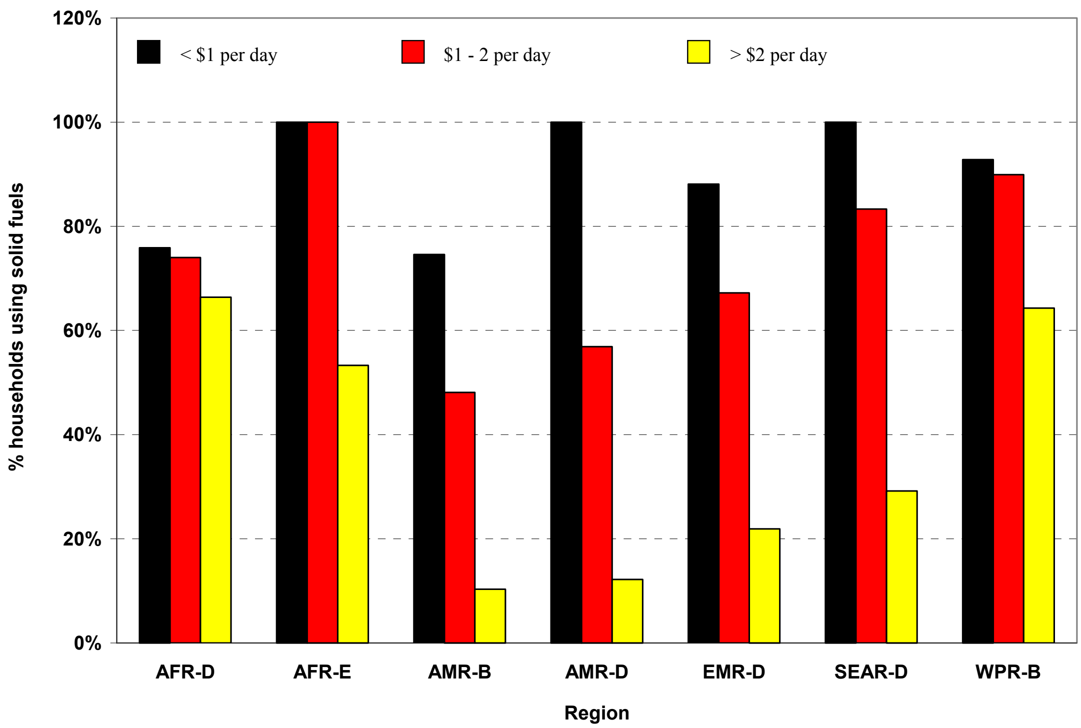


Figure 9: Decreasing prevalence of solid fuel use with increasing household income (source: (13)). See appendix for description of regions.

The correlation between poverty and energy source (i.e. fuel), often formalized in the "energy ladder" framework, has been considered in a number of works (53, 70, 92, 93). The energy ladder framework hypothesizes that households switch to cleaner sources of energy with

[8] While we consider them in separate sections, poverty, gender, and their relationships with resource use are also interrelated (4). Women in households of differing socioeconomic status experience the development and health

increasing income. Since the formulation of this framework, a number of works have illustrated that use of multiple fuels is common across various income groups (24, 79). More broadly, while the energy ladder is a convenient qualitative representation of the correlation between household energy supply and household wealth or social status, its simplification of the social dimensions of energy use motivates a more systematic approach to evaluating the choices of household energy technology for policy purposes. In its simplest form, like many other economic transition frameworks (such as the economic-environment relationship (37)), the energy ladder framework would imply a deterministic view of development and energy that need not hold if the circumstances of social development – including cultural, policy, and infrastructure – are different from those in original formulation. This deterministic formulation can also hinder innovative technological and policy approaches to addressing the energy issues of the poor. As importantly, the energy ladder construct is unable to account for the amount of energy (versus its form) and uncertainty in access to energy both of which are important determinants of the welfare effects of energy (see the experience of the diffusion of agricultural technologies for empirical examples on the importance of technology access and uncertainty (12, 40)).

The above discussion does not imply that income is not a crucial determinant of household energy choice. Rather it is important to treat income not as a deterministic cause of energy transition, but rather as a determinant of additional *freedom* to choose a certain type and quantity fuel (or array of fuels) as well as the technology for fuel utilization. What the household actually does with the extra income will be decided by individual household members – influenced by differentiated gender-based priorities, community and cultural factors, energy and economic infrastructure and barriers, regulatory and political determinants of energy access, and a number

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implications of energy and energy technology in different forms.

of other factors (Table 5) (62, 70). Households may spend extra income on non-energy commodities or services, such as health or education. Even within the energy realm, a household may decide to consume more energy (e.g. purchase more charcoal), switch to a different form of energy (e.g. switch to kerosene or LPG from biomass), switch its source of energy access (e.g. purchase biomass instead of collecting it), or use a mix of energy sources for different purposes (e.g. continue to use biomass for cooking and heating and purchase a photovoltaic unit for lighting).

Table 5: Household energy choices and barriers (adopted from (62, 70))

	Selected determinants of adoption		
Energy source	**Equipment costs**	**Nature of payments**	**Nature of Access ***
Electricity	Very high	Lumpy	Restricted
Bottled gas (LPG, butane, Natural Gas)	High	Lumpy	Often restricted, bulky to transport
Kerosene	Medium	Small	Often restricted in low income areas
Charcoal	Low	Small	Good, dispersed markets and reliable supplies though prices and supplies can vary seasonally
Fuelwood	Low or Zero	Small, zero if gathered	Good, dispersed markets and reliable supplies though prices and supplies can vary seasonally
Crop residues, animal dung	Low or Zero	Small, zero if gathered	Variable: depends on local crops and livestock holding. High opportunity where residues are used as fodder and/or dung is used as fertilizer

* Nature of access refers to ease at which households can choose the fuel without the need for physical and institutional infrastructure

3.2 Energy, gender, and health

While much of the international development literature has attempted to consider the role of intra-household allocation of resources in addition to household level welfare effects, energy is possibly the aspect of development where gender differentials in access to resources and its consequences are most observable (see (22) for a review). At the broadest level, cooking and heating – the most common uses of energy – are handled by women in most households in developing countries. In meeting the energy needs of the household, the woman allocates part of the limited household budget of cash and/or labor to procuring energy resources. When fuels are collected, which can involve walking many kilometers and carrying in excess of 20 kilograms of wood, the burden of work falls disproportionately on woman, who may expend a significant fraction of their daily caloric needs gathering fuel (Figure 10) (72). Therefore, energy scarcity and insecurity, often caused by joint effects of economic and environmental factors, affect the tasks and decisions of female household members, and often lead to the use of less energy or more inferior energy sources (19).

Figure 10: In many regions of developing countries, female household members carry in excess of 20 kilograms of wood for many kilometers and hours each day (photograph by M. Ezzati)

Women, who gather or purchase fuel, cook, and handle fire considerably more frequently than men, also have much higher exposure to the hazards of energy use (10, 32, 100), including respiratory or eye diseases due to indoor smoke, burns, or back pain and injuries from carrying heavy loads. For example, 75% of adult deaths attributable to exposure to indoor air pollution (Table 4) were among women (34, 125).

Increased access to clean energy sources can improve the day-to-day as well as long-term welfare of female household members. Health improvements, and time and/or money saved from energy needs may be used for leisure, participation in formal labor force, education, and community or commercial activities (see Table 2.4 in (93) for a list of such activities). This transfer of resources could be an important mechanism to improve the status of women in developing countries. When considering energy as a tool for improving the status of women, it is essential to note that the economic and social institutions, both inter- and intra-household, that hinder female access to adequate clean sources of energy are often the same that create other gender-based inequalities. In fact, it has been argued that the increased prominence of biomass as an economic and commercial commodity (e.g. as a source of energy for small-scale manufacturing) has attracted local entrepreneurs and business actors – mostly men – driving women to assume more marginal social roles and depend on inferior sources of energy (2, 3, 84). Therefore, for improved energy access and technology to become a tool for increasing social and economic welfare of women, other institutions are also needed including access to credit, labor and product markets, land, and education (99). Furthermore, access to these opportunities can be sustained only if coupled with increased female participation in the social decision making and policy process (5, 15).

4 Energy Development and Public Health

4.1 Technology options

Conventional energy sources based on oil, coal, and natural gas have proven to be highly effective drivers of economic progress, but at the same time damaging to the environment and to human health as described above (46). Over decades of development aid and lending, bi-lateral and multi-lateral development agencies financed numerous conventional fossil-fuel based energy projects and large-scale hydroelectric power in developing countries which resulted in large burden of debts in these countries, had significant impacts on local environment and health, and provided only a small fraction of population with adequate energy services (98). The use of fossil fuel-based energy as the sole or main driver of development is looking increasingly problematic for many reasons, including uncertainty in price and reliability of international energy markets, and their environmental health consequences (see (46) for a discussion).

The potential role of renewable energy technologies (RETs) in transforming global energy use, with a focus on sustainable development and increasing the welfare and health of the global poor, on the other hand is enormous. Energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on a mix of readily available, indigenous resources with potential to result in minimal local environmental damage or net emissions of GHGs if implemented appropriately (see Text Box 2 for a discussion of implementation). A transition to renewables-based energy systems is looking increasingly desirable, and possible, as the costs of solar and wind power systems have dropped substantially in the past 30 years. Most forecasts indicate that costs of renewably produced electricity should continue to decline (Figure 11), while the price of oil and gas continue to fluctuate. If social and environmental costs are included in the estimation of electricity costs, RETs become still more attractive (49, 86, 119).

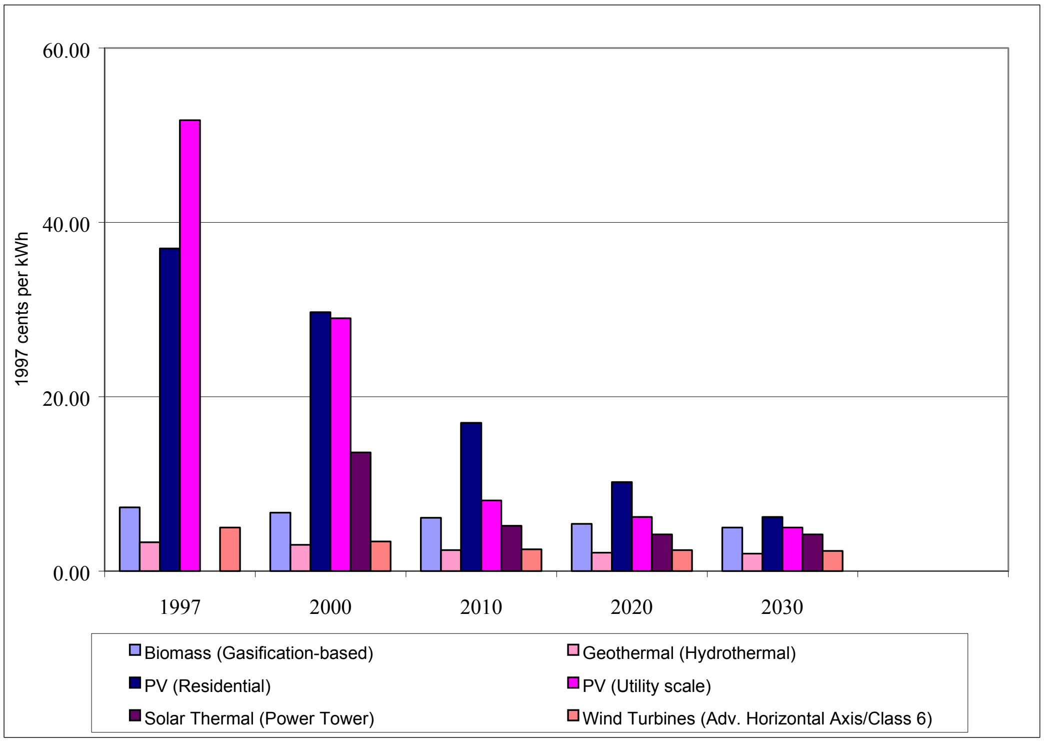

Figure 11: Levelized cost of electricity forecast for renewable energy technologies (source: (49, 118)). Levelized costs account for both capital costs and operation and maintenance.

Renewable energy systems are usually implemented in a small-scale, decentralized model that is inherently conducive to, rather than at odds with, many electricity distribution, cogeneration (combined heat and power), environmental, public health, and capital cost issues. In particular, these systems can have dramatically reduced as well as widely dispersed environmental impacts, rather than larger, more localized effects such as ambient air pollution, acid rain, and ecological degradation. While the recent developments in RETs draw on evidence from industrialized countries, the issues concerning conventional fossil fuel-based energy systems are equally, if not more, important for developing countries. Heavy reliance on imported fossil fuels places a huge burden on the financial resources of developing countries in addition to the environmental and public health issues raised above. Supply constraints and exchange rate fluctuations affect reliability in the energy sector, which inhibits investment and retards economic activity.

Renewable energy sources currently supply between 15% and 20% of the world's total energy demand (56). The supply is dominated by traditional biomass, mostly fuelwood used for household energy needs in developing countries. A major contribution is also from the use of large hydropower, with nearly 20 percent of the global electricity supply being provided by this source. New renewable energy sources (solar energy, wind energy, modern bio-energy, geothermal energy, and small hydropower) are currently contributing about two percent of the global energy mix. In developing nations, renewable energy technologies are increasingly used to address energy shortages and to expand the range of services in both rural and urban areas. In Kenya, for example, over 150,000 small (20 - 100 Wp) solar PV systems have been commercially financed and installed in homes, battery charging stations, and other small enterprises (26). A government program in Mexico has disseminated over 40,000 such systems. In the Inner Mongolian autonomous region of China over 130,000 portable windmills provide electricity to about one-third of the non-grid-connected households in this region (54). Just as some developing countries are bypassing construction of telephone wires by leaping directly to cellular-based systems, so too might they avoid building large, centralized power plants and instead develop decentralized systems. This strategy can also reduce the need for the construction of large power grids, further mitigating the environmental and health costs of electrification.

4.2 Policy instruments [9]

A number of future energy scenario studies have investigated the potential contribution of RETs to global energy supplies, indicating that in the second half of the 21st century their contribution might range from the present figure of nearly 20% to more than 50%. In essence, however, renewable energy technologies face a similar situation confronting any new technology that attempts to dislodge an entrenched technology. For many years, industrialized countries have been “locked-in” to a suite of fossil fuel and nuclear-based technologies, and many secondary systems and networks have been designed and constructed to accommodate these. The transition to RETs, important for local and global economic, environmental, and health benefits, will only be realized if energy projects and policies are evaluated and implemented based on their *overall* social, economic, environmental, and public health merits.

The economic and policy mechanisms needed to support the widespread dissemination and sustainable markets for renewable energy systems have rapidly evolved. In particular, financial markets are realizing the future growth potential of renewable and other new energy technologies, a likely harbinger of the economic reality of truly competitive renewable energy systems. At the same time, important policy gaps for fully utilizing the potential of RETs as a tool for sustainable development remain as described below. [10]

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[9] See (49, 62) for more detailed discussion.

[10] One limitation for increased use has been the intermittent nature of some renewable energy sources, such as wind and solar. One solution to this issue is to develop diversified systems that maximize the contribution of renewable

Leveling the playing field

Despite their limited recent success, renewable energy sources have historically had a difficult time breaking into markets that have been dominated by traditional, large-scale, fossil fuel-based systems. While this is partly because renewable and other new energy technologies have previously had high capital costs relative to more conventional systems and are only now being mass produced, coal, oil, and gas-powered systems have benefited from a range of subtle subsidies over the years. These include expenditures to protect oil exploration and production interests overseas, the costs of railway construction that have enabled economical delivery of coal to power plants, and a wide range of smaller subsidies.

Renewable energy technologies tend to be characterized by relatively low environmental costs. Many of these environmental costs are however "externalities" that are not priced in the market, while others are considered only in certain areas and for certain pollutants. The international effort to limit GHG emissions through the Kyoto Protocol may lead to some form of carbon-based tax, which would internalize some of these costs and benefit the spread of RETs. It is perhaps more likely that concern about local air pollution from fossil-fuel power plants will lead to pollution mitigation efforts because of more immediate and localized benefits, which will promote cleaner renewable systems and potentially also lead to GHG emission reductions (Text Box 1).

Investment in innovation and R&D

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energy sources but that also use clean natural gas and/or biomass-based power generation to provide base-load power when the sun is not shining and the wind is not blowing.

Recent efforts targeting a variety of small-scale traditional, fossil fuel, and renewable energy technologies have resulted in dramatic improvements in performance, marketing, sales and leasing opportunities, and end-user satisfaction in industrialized and developing nations. Examples include the growth of local mini-grids using diesel or renewable energy sources, improved efficiency cookstoves, photovoltaic solar home systems, wind-turbines for household and micro-enterprise applications, micro-hydro generators, and biomass energy systems. Some of these technologies have already had a significant impact on local patterns of energy use, economic activity, and the environment (60). The options for promoting the sustainable introduction of clean energy technologies are tightly connected with the capacity for energy research, development, demonstration, and deployment in developing countries.

Despite the widely-acknowledged benefits of energy research and development, national systems of innovation, particularly in the energy sector, have proven difficult to maintain. Among the problems that plague the institutions that support research and implementation of small-scale and decentralized energy technologies and management methods is lack of steady funding. Equally critical, however, are the paucity of training venues, technology and information exchange, and technology standards for these often-overlooked energy systems (67, 83, 117). In addition, there is a systematic lack of micro-credit available to foster locally designed and implemented commercialization efforts. In some areas the governments may even see stand-alone and or mini-grid systems as unwelcome competitors to national utilities.

Research and development (R&D) requires long-term commitment because the time-scale to develop both new technologies and, more critically, generations of innovators takes years or decades. The results are often diffuse, with both specific innovations and individuals moving freely about, on occasion leaving the nurturing nation. These features, particularly in poorer nations, make R&D capacity seen largely as a luxury, rarely supported against the other and often more apparently pressing needs of energy development.

An area that particularly suffers from the lack of research is analysis of the relationship between renewable energy projects and the social and economic contexts in which they are embedded. All too often projects are planned, implemented, or evaluated based on unexamined assumptions about local conditions, and the social and economic consequences of the project. Broader discussions of the role of traditional renewable (i.e. biomass), or stand-alone fossil-fuel energy in rural development strategies under conditions of economic globalization are rare, despite their obvious importance to questions such as rural electrification, and the impacts of linking remote areas to the formal economy.

The neglect of energy R&D capacity to meet global and national energy needs is the result of the combination of two powerful forces: the vulnerable and often neglected domestic capacity for innovation in developing nations, and the lack of sustained support for energy research and development capacity by industrialized nations (78). The commitments made during World Summit on Sustainable Development in Johannesburg should provide a critical opportunity to bring attention to this under-investment, and to build a full understanding of the need and importance of energy R&D (60).

5 Conclusions

We have described some of the linkages between public health and energy. Despite its close linkages with health, most energy policies and programs in the developing world fundamentally remain in the realm of social and economic development policies. The challenge to both energy and public health researchers and practitioners is therefore to incorporate the close links between the two sectors in the design of energy policies and programs that increase welfare and minimize the negative health consequences that those activities might entail (29), such as those discussed for RETs.

Acknowledgement

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Text Box 1

Integrated environmental strategies for air pollution and greenhouse gas (GHG) reductions in Chile

The integrated environmental strategies in Chile provide an example of the interaction of measures to abate air pollution and measures to mitigate GHG emissions. Two types of analysis were conducted: a global analysis, in which the health benefits associated with a GHG mitigation scenario were estimated, and a detailed intervention analysis, in which both GHG and local air pollution reductions are estimated for specific interventions, and their social benefits compared.

For the first analysis, a moderate "climate policy" scenario was considered. This scenario has been developed for the Chilean National Environmental Commission, and considered only non-positive costs measures, like efficiency improvements in the industrial and residential sectors. The level of carbon abatement of this scenario is modest, 13% from the business-as-usual scenario. Emission reductions of local air pollutants (CO, SO_2, VOCs, NO_X, re-suspended dust and PM_{10}) were estimated from emission factors recommended by the IPCC. The proportional reductions were applied uniformly to major urban areas of Chile that had data on particulate matter concentrations. The health benefits due to air pollution abatement were estimated using figures derived previously for the cost-benefit analysis of Santiago's Decontamination Plan, transferred to the different cities taking into consideration local demographic and income data. The Santiago estimates were obtained using the damage function approach, based on some local epidemiological studies, and on local health and demographic data. Unit social values for the effects were estimated locally (for cost of treatment and lost productivity values) or extrapolated from US values (mainly for willingness-to-pay (WTP) values) using the ratio of per-capita income and an income elasticity of 1. The average benefits of emission abatement (in 1997 US$ per ton) were an estimated 1,800 (95% CI 1,200 – 2300) for NO_X, 3,000 (95% CI 2,100 – 3900) for SO2, 31,900 (95% CI 21,900 – 41,900) for PM, and 630 (430 – 830) for re-suspended dust. These benefits were extrapolated over time using the expected population and per-capita income growth. Dividing the health benefits accrued from the local air pollutant emissions reductions by the amount of carbon abated, average ancillary benefits of 69 (95% CI 30 – 260) and 104 (95% CI 50 – 380) US$ per ton of carbon abated were estimated for the years 2010 and 2020.

The second analysis involved detailed examination of specific mitigation measures in Santiago. Most of the measures considered were primarily aimed at local air pollution abatement (e.g. technology changes in public transport buses) but some were energy efficiency measures. The emissions reductions of both GHG and local air pollutants were estimated from emission factors (some derived locally) and changes in activity levels. Figure 12 shows the relationship between reductions in carbon equivalent and $PM_{2.5}$ precursors (the percentage change was based on the relative contribution of unit pollutant emissions to ambient concentrations during Santiago's winter).

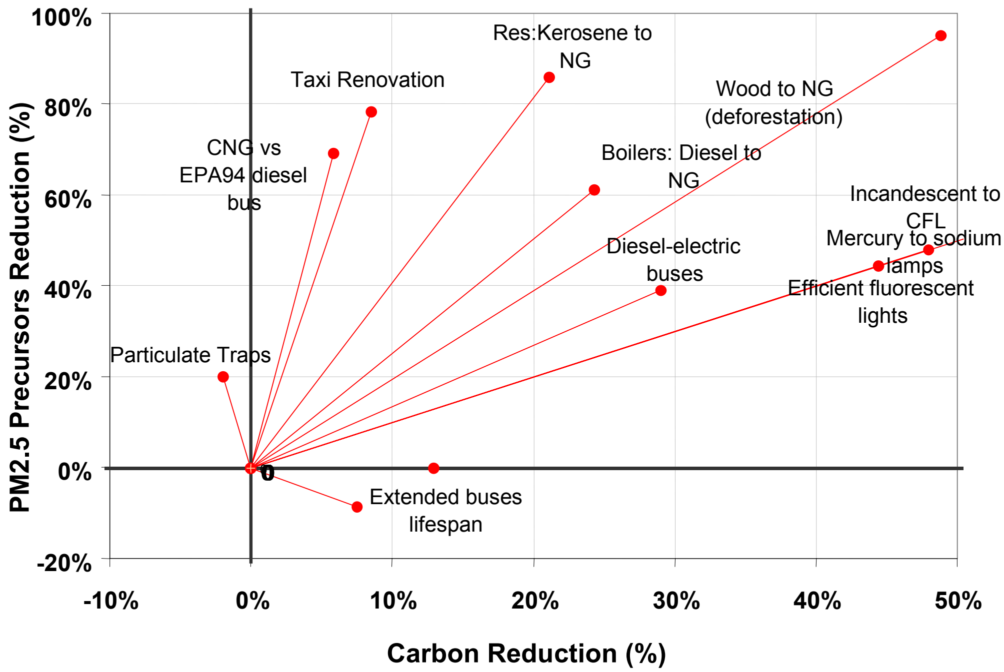

Figure 12: Percentage reductions in CO_2 equivalent and in local air pollutants for selected measures

As seen in the figure, most measures have a bigger local air pollution reduction than carbon reduction. Two measures (conversion of existing diesel buses (EPA91) to compressed natural gas (CNG)), and extended life-span of existing diesel buses) have zero or negative air pollution reductions, while particulate traps for diesel buses have negative carbon reductions.

Next, the benefits from local air pollution abatement and carbon reduction were compared. Values of 20 and 50 US$/tCe were considered for valuing the carbon reductions, while the previously described values were considered for local air pollutant reductions. A comparison of the benefits shows that health benefits are generally much higher than carbon benefits. For the fuel switching measures, carbon benefits were estimated as 9% to 28% of the health benefits (the latter figure for the 50 US$/tCe case for diesel to natural gas switch in boilers). In the transportation sector, the ratio was estimated from zero to 13% for hybrid electric buses. The electricity savings measures varied from 5% to 12%. In terms of offsetting some of the costs of the measures in the transport sector, at 20US$/tCe, carbon credits would account for just 0.6% of the annual costs of CNG buses, for 2.6% for the CNG conversion of existing buses, and for 15 % of those of hybrid-electric buses. The figures increased to 1.5%, 6% and 37% if carbon reductions were valued at 50 US$/tCe.

These results show that the local pollution health benefits of interventions that simultaneously reduce GHG emissions are significant, both for the scenario analysis and for the mitigation measure analysis. The public health benefits of carbon reduction measures can offset most of the cost of GHG reduction. However, for most measures analyzed, the public health benefits were an order of magnitude greater than the benefits from carbon reduction. Also, the cost offsets due to potential carbon credits were limited from a few percent up to 36% in the best case. This suggests that the main driver for air pollution policy is likely to remain local concerns, such as public health issues.

Text Box 2

Complex energy-environment-health linkages and policy needs: charcoal in sub-Saharan Africa

The results in Figure 8 show that, on average, charcoal stoves have higher GHG emissions than woodstoves when the radiative forcing of the emitted gases is included in the calculation. The GHG picture becomes still bleaker for charcoal when one considers the entire life cycle of the fuel. Unlike woodfuel, which involves few, if any, GHG emissions prior to its use in the stove, charcoal end-use only represents a fraction of the net GHG emissions from the charcoal life cycle. Charcoal production, particularly in developing countries where it is practiced with minimal technical inputs, is essentially combustion starved of sufficient oxygen, which results in very high emissions of a range of pollutants (18, 27, 89).

Although emissions from charcoal production and end-use are associated with much higher GHG emissions than firewood, charcoal consumption can offer public health benefits over fuelwood, especially when clean-burning cooking fuels such as kerosene and natural gas are inaccessible or unaffordable. In rural Kenya, for example, a transition from using wood in an open (3-stone) fire to charcoal would reduce PM10 exposure of household members by 75%-95% on average for different demographic groups resulting in a 21-44% decrease in childhood acute lower respiratory infections (ALRI), as well as significant adult health benefits (31).

Fuel switching and charcoal markets

Nations, like Kenya, that contribute very little to the total global release of GHGs (<0.1%), probably stand to gain more from the immediate health benefits associated with fuel substitution from wood to charcoal than they do from discouraging its use because it carries a heavy GHG burden, especially given the increasing realization of the relevance of the health issues of the global poor for meeting development goals (124). In Kenya, as in many other sub-Saharan African countries, charcoal is often readily available, can be purchased in small quantities and requires no expensive equipment to use. For these reasons, and because it is relatively clean, safe, affordable, and storable, charcoal is the preferred fuel for most urban households as well as an increasing number of rural families. Charcoal has few direct substitutes in poor urban and peri-urban areas of many sub-Saharan African countries (81). In Kenya for example, over 80% of the urban population, some 1.4 million households, use charcoal as their primary cooking fuel (66). Therefore, despite the local (and global) environmental effects described above, attempts to curtail charcoal consumption are likely to be met with stiff public resistance, in the absence of policies that are specifically designed to increase access to alternative household fuels like kerosene and LPG. However, if the decision is made to promote charcoal consumption because of its public health benefits, steps must also be taken to ensure a sustainable supply of wood or an alternative biomass feedstock.

Charcoal markets in many sub-Saharan African countries operate within a complex political economy that can be hard to characterize and still more difficult to regulate. Even where regulations have been put forth, as in some West African countries, they are often poorly enforced and/or circumvented by powerful interest groups who control one or more parts of the commodity chain (see (96, 97) for a description of Senegal's charcoal supply chain and the ways in which regulations have been circumvented by wealthy merchants). In Kenya, which has one of the highest rates of per capita charcoal consumption in Africa, charcoal production has very ambiguous legal status that discourages investment in efficiency and conservation. The legality of charcoal production depends on the tenure relations of the land on which it is produced, varying across public, private, and communal landholdings. Transportation of charcoal requires a permit, but the process of accessing permits is inconsistent and poorly understood. Despite these barriers, tens of thousands of people make their living by participating in one or more aspect of the charcoal supply chain and revenues from the charcoal trade are thought to exceed US$ 300 million (28).

Sustainable charcoal production will be difficult to ensure where, like Kenya, the regulatory structure is poorly articulated and inconsistently enforced. In such situations, trees are undervalued and the cost of tree replacement is not internalized in the price of the commodity; charcoal is made from natural forests or woodlands, which are slow to recover, or from woodland cleared for agriculture so that the tree cover is permanently removed. Without coherent land management policies promoting sustainable production, the public health benefits that charcoal may provide will come at large environmental costs. In order to take advantage of the potential benefits that increased charcoal consumption can bring while minimizing the negative impacts associated with its production and use, a much more coherent policy framework is required. Such a framework would legalize and regulate charcoal production, and ensure that sustainable levels and methods (52) of production are maintained while consumer needs are met with prices that reflect the true cost of production: including harvesting and regeneration, conversion, transportation and sales.

Carbon credits to mitigate GHG emissions

While charcoal consumption carries a larger burden of GHG emissions than firewood use, it also has more potential to attract investment in GHG mitigation activities. Emissions from charcoal can be reduced at both the production and consumption components of its life cycle. Emission reductions in charcoal end-use can be achieved by disseminating improved (high-efficiency and low-emissions) charcoal stoves, which reduce emissions by improving combustion efficiency. Further, users generally should see substantial fuel savings, , which leads to household benefits in addition to GHG reductions. Such charcoal stoves have been widely disseminated and adopted in urban Kenya for example, though they are still short of saturation levels and offer potential for wider dissemination, especially in both urban and rural areas (61). In addition, very little research has been done to assess field performance of stoves currently on the market for household use and there are some fears that many substandard stoves have crept into the market since donors and non-governmental groups have stopped participating in stove design and dissemination projects (64).

While some research has addressed charcoal *consumption* in developing countries, researchers are only now beginning to consider charcoal *production* in sub-Saharan Africa and elsewhere. Most charcoal production in sub-Saharan Africa occurs in earth mounds, which vent the products of incomplete combustion directly to the atmosphere. Arguably, larger GHG emission reductions and energy conversion efficiency improvements can be achieved by changing charcoal production practices than by focusing on charcoal consumption both because the activity is more centralized and because roughly 70% of non-CO_2 GHG emissions attributable to the charcoal life-cycle result from the production process. To our knowledge, no attempt has been made to assess the costs, benefits and institutional requirements of these types of GHG emissions reduction activities.

In summary, when assessing emissions and the potential for emissions reductions in energy-related activities in developing countries, it is particularly important to take an integrated approach by considering the entire life cycle of the fuel, as well as its full public health and welfare effects. Further, when considering energy end-use, it is essential to explore all of the factors that influence household energy consumption and potentially lead to great variability among different households (9).

Appendix

Global Burden of Disease (GBD) sub-regions (source: (125)).

WHO Region	Mortality stratum *	Countries	Population (thousands)
African Region (AFR)	**D**	Algeria, Angola, Benin, Burkina Faso, Cameroon, Cape Verde, Chad, Comoros, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Madagascar, Mali, Mauritania, Mauritius, Niger, Nigeria, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Togo	294,078
	E	Botswana, Burundi, Central African Republic, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Kenya, Lesotho, Malawi, Mozambique, Namibia, Rwanda, South Africa, Swaziland, Uganda, United Republic of Tanzania, Zambia, Zimbabwe	345,515
Region of the Americas (AMR)	**A**	Canada, Cuba, United States of America	325,183
	B	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Brazil, Chile, Colombia, Costa Rica, Dominica, Dominican Republic, El Salvador, Grenada, Guyana, Honduras, Jamaica, Mexico, Panama, Paraguay, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela	430,932
	D	Bolivia, Ecuador, Guatemala, Haiti, Nicaragua, Peru	71,230
Eastern Mediterranean Region (EMR)	**B**	Bahrain, Cyprus, Iran (Islamic Republic of), Jordan, Kuwait, Lebanon, Libyan Arab Jamahiriya, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates	139,059
	D	Afghanistan, Djibouti, Egypt, Iraq, Morocco, Pakistan, Somalia, Sudan, Yemen	342,576
European Region (EUR)	**A**	Andorra, Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Slovenia, Spain, Sweden, Switzerland, United Kingdom	411,889
	B	Albania, Armenia, Azerbaijan, Bosnia and Herzegovina, Bulgaria, Georgia, Kyrgyzstan, Poland, Romania, Slovakia, Tajikistan, The Former Yugoslav Republic of Macedonia, Turkey, Turkmenistan, Uzbekistan, Yugoslavia	218,458
	C	Belarus, Estonia, Hungary, Kazakhstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Ukraine	243,184
South-East Asia Region (SEAR)	**B**	Indonesia, Sri Lanka, Thailand	293,819
	D	Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Maldives, Myanmar, Nepal	1,241,806
Western Pacific Region (WPR)	**A**	Australia, Brunei Darussalam, Japan, New Zealand, Singapore	154,354
	B	Cambodia, China, Cook Islands, Fiji, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Micronesia (Federated States of), Mongolia, Nauru, Niue, Palau, Papua New Guinea, Philippines, Republic of Korea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Viet Nam	1,532,933

* **A**: very low child mortality and very low adult mortality; **B**: low child mortality and low adult mortality; **C**: low child mortality and high adult mortality; **D**: high child mortality and high adult mortality; **E**: high child mortality and very high adult mortality. High-mortality developing: AFR-D, AFR-E, AMR-D, EMR-D, and SEAR-D (population 2.295 billion). Lower-mortality developing regions: AMR-B, EMR-B, SEAR-B, WPR-B (population 2.397 billion). Developed regions: AMR-A, EUR-A, EUR-B, EUR-C, and WPR-A (population 1.353 billion).

References

1. Agarwal B. 1983. Diffusion of Rural Innovations: Some Analytical Issues and the Case of Wood-burning Stoves. *World Development* 11: 359-76
2. Agarwal B. 1986. *Cold hearths and barren slopes : the woodfuel crisis in the Third World*. London: Zed Books
3. Agarwal B. 1994. *A Field of Their Own: Gender and Land Rights in South India*. Cambridge: Cambridge University Press
4. Agarwal B. 1997. Gender, Environment, and Poverty Interlinks: Regional Variations and Temporal Shifts in Rural India. *World Development* 25: 23-52
5. Agarwal B. 2001. Participatory Exclusions, Community Forestry, and Gender: An Analysis for South Asia and a Conceptual Framework. *World Development* 29: 1623-48
6. Ahmad K. 2002. Pollution cloud over south Asia is increasing ill health. *Lancet* 360: 549
7. Arungu-Olende S. 1984. Rural Energy. *Natural Resources Forum* 8: 117-26
8. Baer P, Harte J, Haya B, Herzog AV, Holdren J, et al. 2000. Equity and Greenhouse Gas Responsibility. *Science* 289: 2287
9. Bailis R, Ezzati M, Kammen DM. 2003. Greenhouse Gas Implications of Household Energy Technology in Kenya. *Environmental Science and Technology* 37: 2051-9
10. Balakrishnan K, Sankar S, Parikh J, Padmavathi R, Srividya K, et al. 2002. Daily average exposures to respirable particulate matter from combustion of biomass fuels in rural households of southern India. *Environmental Health Perspectives* 110: 1069-75
11. Barnes DF, Openshaw K, Smith KR, van der Plas R. 1994. *What Makes People Cook with Improved Biomass Stoves? A Comparative International Review of Stove Programs*, The World Bank, Washington, DC
12. Barnett V, Payne R, Steiner JR, eds. 1995. *Agricultural Sustainability in Economic, Environmental, and Statistical Terms*. London: John Wiley and Sons
13. Blakely T, Hales S, Kieft, Wilson N, Woodward A. 2004. Distribution of Risk Factors by Poverty. In *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, ed. M Ezzati, AD Lopez, A Rodgers, CJL Murray. Geneva: World Health Organization
14. Bloom D, Zaidi AKM. 2004. The Demographic Impact of Biomass Fuel Use. *Applied Environmental Science and Public Health* in-press
15. Bourque SC, Warren KB. 1990. Access Is Not Enough: Gender Perspectives on Technology and Education. In *Persistent Inequalities*, ed. I Tinker. Oxford: Oxford University Press
16. Boy E, Bruce N, Delgado H. 2002. Birth Weight and Exposure to Kitchen Wood Smoke During Pregnancy in Rural Guatemala. *Environmental Health Perspectives* 110: 109-14
17. Bradley PN, Campbell BM. 1998. Who Plugged the Gap? Re-Examining the Woodfuel Crisis in Zimbabwe. *Energy and Environment* 9: 235-55
18. Brocard D, Lacaux C, Lacaux JP, Kouadio G, Yoboue V. 1996. Emissions from the combustion of biofuels in Western Africa. In *Biomass Burning and Global Change*, ed. JS Levine, pp. 350-60. Cambridge, MA: MIT Press
19. Brouwer ID, Hoorweg JC, van Liere MJ. 1997. When Households Run out of Fuel: Responses of Rural Households to Decreasing Fuelwood Availability, Ntcheu District, Malawi. *World Development* 25: 255-66

20. Bruce N, Perez-Padilla R, Albalak R. 2000. Indoor Air Pollution in Developing Countries: A Major Environmental and Public Health Challenge. *Bulletin of the World Health Organization* 78: 1078-92
21. Casman E, Dowlatabadi H, eds. 2002. *The Contextual Determinants of Malaria*. Washington, DC: RFF Press
22. Cecelski EW. 1995. From Rio to Beijing. *Energy Policy* 23: 561-75
23. Cohen A, Anderson R, Gutschmidt K, Krzyzanowski M, Künzli N, et al. 2004. Urban Ambient Air Pollution. In *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, ed. M Ezzati, AD Lopez, A Rodgers, CJL Murray. Geneva: World Health Organization
24. Davis M. 1998. Rural Household Energy Consumption: The Effects of Access to Electricity - Evidence from South Africa. *Energy Policy* 26: 207-17
25. De Koning HW, Smith KR, Last JM. 1985. Biomass Fuel Combustion and Health. *Bulletin of the World Health Organization* 63: 11-26
26. Duke RD, Jacobson A, Kammen DM. 2002. Photovoltaic Module Quality in the Kenyan Solar Home Systems Market. *Energy Policy* 30: 477-99
27. Dutt GS, Ravindranath NH. 1993. Bioenergy: Direct Applications in Cooking. In *Renewable Energy: Sources for Fuels and Electricity*, ed. T Johansson, H Kelly, AKN Reddy, RH Williams, pp. 653-97. Washington, DC: Island Press
28. Ecoforum. 2002. Hot and Dirty: Inside Kenya's 23 Billion Shilling Charcoal Industry. *EcoForum (Nairobi)* 25: 16-22
29. Ezzati M. 2003. Complexity and Rigour in Assessing the Health Dimensions of Sectoral Policies and Programs. *Bulletin of the World Health Organization* 81: 458-9
30. Ezzati M, Kammen DM. 2001. Indoor Air Pollution from Biomass Combustion as a Risk Factor for Acute Respiratory Infections in Kenya: An Exposure-Response Study. *Lancet* 358: 619-24
31. Ezzati M, Kammen DM. 2002. Evaluating the Health Benefits of Transitions in Household Energy Technology in Kenya. *Energy Policy* 30: 815-26
32. Ezzati M, Kammen DM. 2002. The Health Impacts of Exposure to Indoor Air Pollution from Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs. *Environmental Health Perspectives* 110: 1057-68
33. Ezzati M, Kammen DM. 2002. Household Energy, Indoor Air Pollution and Health in Developing Countries: Knowledge Base for Effective Intervention. *Annual Review of Energy and the Environment* 27: 233-70
34. Ezzati M, Lopez AD, Rodgers A, Vander Hoorn S, Murray CJL, Comparative Risk Assessment Collaborative Group. 2002. Selected Major Risk Factors and Global and Regional Burden of Disease. *Lancet* 360: 1347-60
35. Ezzati M, Mbinda BM, Kammen DM. 2000. Comparison of Emissions and Residential Exposure from Traditional and Improved Biofuel Stoves in Rural Kenya. *Environmental Science and Technology* 34: 578-83
36. Ezzati M, Saleh H, Kammen DM. 2000. The Contributions of Emissions and Spatial Microenvironments to Exposure to Indoor Air Pollution from Biomass Combustion in Kenya. *Environmental Health Perspectives* 108: 833-9
37. Ezzati M, Singer BH, Kammen DM. 2001. Towards an Integrated Framework for Development and Environment: The Dynamics of Environmental Kuznets Curves. *World Development* 29: 1421-34

38. Ezzati M, Vander Hoorn S, Rodgers A, Lopez AD, Mathers CD, et al. 2003. Estimates of global and regional potential health gains from reducing multiple major risk factors. *Lancet* 362: 271-80
39. Finkelman RB, Belkin HE, Zheng B. 1999. Health impacts of domestic coal use in China. 96: 3427-31
40. Frossard D. 1994. *Peasant Science: Farmer Research and Philippine Rice Development (Ph.D. Thesis)*. Ph.D. Thesis thesis. University of California, Irvine
41. Goldemberg J, ed. 2000. *World Energy Assessment: Energy and the Challenge of Sustainability*. New York: United Nations Development Programme
42. Goldemberg J, Johansson TB, eds. 1995. *Energy as an Instrument for Social Change*. New York: United Nations Development Programme
43. Goldemberg J, Johansson TB, eds. 2002. *Energy for Sustainable Development: A Policy Action Agenda*. New York: United Nations Development Programme
44. Goldemberg J, Johansson TB, Reddy AKN, Williams RH. 1985. Basic Needs and More with One Kilowatt Per Capita. *AMBIO* 14: 190-200
45. Green C, Vimmerstedt L, Renne J, Benioff R, eds. 2000. *Developing Country Case-Studies: Integrated Strategies for Air Pollution and Greenhouse Gas Mitigation.* Washington, DC:: USEPA (Prepared by NREL for the USEPA Office of Atmospheric Programs)
46. Hall C, Tharakan P, Hallock J, Cleveland C, Jefferson M. 2003. Hydrocarbons and the evolution of human culture. *Nature* 426: 318-22
47. Hall DO, Rosillo-Calle F, Williams RH, Woods J. 1993. Biomass for Energy: Supply Prospects. In *Renewable Energy: Sources for Fuels and Electricity*, ed. TB Johansson, e al., pp. 594-651. Washington, DC: Island Press
48. Hay SI, Cox J, Rogers DJ, Randolph SE, Stern DI, et al. 2002. Climate change and the resurgence of malaria in the East African highlands. *Nature* 415: 905-9
49. Herzog AV, Lipman TE, Edwards JL, Kammen DM. 2001. Renewable Energy: A Viable Choice. *Environment* 43: 8-20
50. Hoek G, Brunekreef B, Goldbohm S, Fischer P, van den Brandt PA. 2002. Association between mortality and indicators of traffic-related air pollution in the Netherlands: a cohort study. *Lancet* 360: 1203-9
51. Holgate ST, Samet JM, Koren HS, Maynard RL, eds. 1999. *Air Pollution and Health*. London: Academic Press
52. Hosier RH. 1993. Charcoal Production and Environmental Degradation: Environmental History, Selective Harvesting, and Post-Harvest Management. *Energy Policy* 21: 491-509
53. Hosier RH, Dowd J. 1987. Household Fuel Choice in Zimbabwe. *Resources and Energy* 9: 347-61
54. Intergovernmental Panel on Climate Change (IPCC). 2000. *Methodological and Technological Issues in Technology Transfer*. Cambridge, UK and New York, USA: Cambridge University Press
55. Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: The Scientific Basis*. Cambridge, UK and New York, USA: Cambridge University Press
56. International Energy Agency (IEA). 2002. *World Energy Outlook 2002*. Paris: International Energy Agency
57. Jacob DJ, Logan JA, Murti PP. 1999. Effect of rising Asian emissions on surface ozone in the United States. *Geophysical Research Letters* 26

58. Kammen DM. 1995. Cookstoves for the Developing World. *Scientific American* 273: 63-7
59. Kammen DM. 1995. From Energy Efficiency to Social Utility: Improved Cookstoves and the *Small is Beautiful* Model of Development. In *Energy as an Instrument for Social Change*, ed. J Goldemberg, TB Johansson. New York: United Nations Development Programme
60. Kammen DM. 1999. Bringing Power to the People: Promoting Appropriate Energy Technologies in the Developing World. *Environment* 41: 10-5, 34-41
61. Kammen DM. 2001. Research, development, and commercialization of the Kenya ceramic jiko. In *Technology, Humans, and Society: toward a Sustainable World*, ed. RC Dorf. San Diego: Academic Press
62. Kammen DM, Bailis R, Herzog AV. 2001. *Clean Energy for Development and Economic Growth: Biomass and Other Renewable Energy Options to Meet Energy and Development Needs in Poor Nations*, United Nations Development Program, New York
63. Karekezi S. 1994. Disseminating Renewable Energy Technologies in Sub-Saharan Africa. *Annual Review of Energy and Environment* 19: 387-421
64. Karekezi S, Ranja T. 1997. *Renewable Energy Technologies in Africa*. London: Zed Books
65. Kartha S. 2001. Biomass sinks and biomass energy: key issues in using biomass to protect the global climate. *Energy for Sustainable Development* 5: 10-6
66. Kenya Ministry of Energy. 2002. *Study on Kenya's Energy Demand, Supply and Policy Strategy for Households, Small Scale Industries and Service Establishments: Final Report*. Nairobi: KAMFOR Company Limited
67. Kozloff KL. 1995. Rethinking Development Assistance for Renewable Electricity Sources. *Environment* 37: 6 - 15, 32 - 8
68. Krugmann H. 1987. *Review of Issues and Research Relating to Improved Cookstoves. Rep. IDRC-MR152e*, International Development Research Centre, Ottawa
69. Krzyzanowski M, Schwela D. 1999. Patterns of Air Pollution in Developing Countries. In *Air Pollution and Health*, ed. ST Holgate, JM Samet, HS Koren, RL Maynard. San Diego,CA: Academic Press
70. Leach G. 1992. The Energy Transition. *Energy Policy* 20: 116-23
71. Leach G, Mearns R. 1988. *Beyond the Woodfuel Crisis: People, Land, and Trees in Africa*. London: Earthscan
72. Levine JA, Weisell R, Chevassus S, Martinez CD, Burlingame B, Coward WA. 2001. The Work Burden of Women. *Science* 294: 812
73. Levine JS, Cofer WRI, al. e. 1995. Biomass Burning: A Driver for Global Change. *Environmental Science and Technology* 29: 120A-5A
74. Levy JI, Houseman EA, Ryan L, Richardson D, Students from the 1998 Summer Program in Biostatistics, Spengler JD. 2000. Particle Concentrations in Urban Microenvironments. *Environmental Health Perspectives* 108: 1051-7
75. Levy JI, Houseman EA, Spengler JD, Loh P, Ryan L. 2001. Fine particulate matter and polycyclic aromatic hydrocarbon concentration patterns in Roxbury, Massachusetts: a community-based GIS analysis. *Environmental Health Perspectives* 109: 341-7
76. Li Q, Jacob DJ, Bey I, Palmer PI, Duncan BN, et al. 2002. Transatlantic Transport of Pollution and its Effects on Surface Ozone in Europe and North America. *Journal of Geophysical Research, in press*

77. Manibog FR. 1984. Improved Cooking Stoves in Developing Countries: Problems and Opportunities. *Annual Review of Energy* 9: 199-227
78. Margolis RM, Kammen DM. 1999. Underinvestment: The Energy Technology and R&D Policy Challenge. *Science* 285: 690-3
79. Masera OR, Saatkamp BD, Kammen DM. 2000. From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development* 28: 2083-103
80. May J, Norton A. 1997. A Difficult Life: The Experiences and Perceptions of Poverty in South Africa. *Social Indicators Research* 41: 95-118
81. Milukas V. 1993. Energy for Secondary Cities: The Case of Nakuru, Kenya. *Energy Policy* 21: 543-58
82. Murray CJL, Lopez AD, eds. 1996. *The Global Burden of Disease*. Cambridge, MA: Harvard School of Public Health (on behalf of the World Health Organization and the World Bank)
83. Mwandosya MJ, Luhanga ML. 1993. Energy and Development in Tanzania: Issues and Perspectives.
84. Naughton-Treves L, Chapman CA. 2002. Fuelwood Resources and Forest Regeneration on Fallow Land in Uganda. *Journal of Sustainable Forestry* 14: 19-32
85. O'Neill MS, Jerrett M, Kawachi I, Levy JI, Cohen AJ, et al. 2003. Health, wealth and air pollution: Advancing theory and methods. *Environmental Health Perspectives* in-press
86. Ottinger RL. 1991. *Environmental Costs of Electricity*. New York: Oceana Publications
87. Ozkaynak H, Spengler J. 1996. The Role of Outdoor Particulate Matter in Assessing Total Human Exposure. In *Particles in Out Air: Concentrations and Health Effects*, ed. R Wilson, JD Spengler. Cambridge, MA: Harvard University Press
88. Patz JA, McGeehin MA, Bernard SM, Ebi KL, Epstein PR, et al. 2000. The Potential Health Impacts of Cimate Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the US National Assessment. *Environmental Health Perspectives* 108: 367-76
89. Pennise D, Smith KR, Kithinji JP, Rezende ME, Raad TJ, et al. 2001. Emissions of Greenhouse Gases and Other Airborne Pollutants from Charcoal-Making in Kenya and Brazil. *Journal of Geophysical Research-Atmosphere* 106: 24143-55
90. Perlin SA, Wong D, Sexton K. 2001. Residential Proximity to Industrial Sources of Air Pollution: Interrelationships among Race, Poverty, and Age. *Journal of the Air and Waste Management Association* 51: 406-21
91. Pope CA, III, Burnett RT, Thun MJ, Calle EE, Krewski D, et al. 2002. Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *Journal of American Medical Association* 287: 1132-41
92. Reddy AKN. 2000. Energy and Social Issues. In *World Energy Assessment: Energy and the Challenge of Sustainability*, ed. J Goldemberg. New York: United Nations Development Programme
93. Reddy AKN, Williams RH, Johansson TB, eds. 1996. *Energy after Rio: Prospects and Challenges*. New York: United Nations Publications
94. Reiter P. 2001. Climate Change and Mosquito-Borne Diseases. *Environmental Health Perspectives* 109: 141-61
95. Reiter P, Lathrop S, Bunning M, Biggerstaff B, Singer D, et al. 2003. Texas lifestyle limits transmission of dengue virus. *Emerg Infect Dis* 9: 86-9

96. Ribot JC. 1993. Forestry Policy and Charcoal Production in Senegal. *Energy Policy* 21: 559-85
97. Ribot JC. 1995. From Exclusion to Participation: Turning Senegal's Forestry Policy Around? *World Development* 23: 1587-99
98. Rich B. 1994. *Mortgaging the Earth: The World Bank, Environmental Impoverishment, and the Crisis of Development*. Boston, MA: Beacond Press
99. Safilios-Rothschild C. 1985. The Persistence of Women's Invisibility in Agriculture: Theoretical and Policy Lessons from Lesotho and Sierra Leone. *Economic Development and Cultural Change*: 298-317
100. Saksena S, Prasad R, Pal RC, Joshi V. 1992. Patterns of Daily Exposure to TSP and CO in the Garhwal Himalaya. *Atmospheric Environment* 26A: 2125-34
101. Sarangapani R, Wexler AS. 1999. Modeling Aerosol Bolus Dispersion in Human Airways. *Journal of Aerosol Science* 30: 1345 - 62
102. Sexton K, Adgate JL. 1999. Looking at Environmental Justice from an Environmental Health Perspective. *Journal of Exposure Analysis and Environmental Epidemiology* 9: 3-8
103. Sexton K, Gong H, Jr., Bailar JC, 3rd, Ford JG, Gold DR, et al. 1993. Air Pollution Health Risks: Do Class and Race Matter? *Toxicology and Industrial Health* 9: 843-78
104. Shen X, Rosen JF, Guo D, Wu S. 1996. Childhood Lead Poisoning in China. *The Science of the Total Environment* 181: 101-9
105. Smith KR. 1987. *Biofuels, Air Pollution, and Health: A Global Review*. New York: Plenum Press
106. Smith KR. 1988. Air Pollution: Assessing Total Exposure in Developing Countries. *Environment* 30: 16-34
107. Smith KR. 1991. Aocating Responsibility for Global Warming: The Natural Debt Index. *Ambio* 20: 95-6
108. Smith KR. 1993. Fuel Combustion, Air Pollution Exposure, and Health: Situation in Developing Countries. *Annual Review of Energy and Environment* 18: 529-66
109. Smith KR. 2002. In praise of petroleum? *Science* 298: 1847
110. Smith KR, Mehta S, Feuz M. 2002. *The Global Burden of Disease from Indoor Air Pollution: Results from Comparative Risk Assessment*. Presented at Indoor Air 2002: Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Monterey, CA
111. Smith KR, Mehta S, Feuz M. 2003. Indoor Air Pollution from Household Solid Fuel Use. In *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, ed. M Ezzati, AD Lopez, A Rodgers, CJL Murray. Geneva: World Health Organization
112. Smith KR, Metha S, Feuz M. 2004. Indoor air pollution from household use of solid fuels. In *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, ed. M Ezzati, AD Lopez, A Rodgers, CJL Murray. Geneva: World Health Organization
113. Smith KR, Samet JM, Romieu I, Bruce N. 2000. Indoor Air Pollution in Developing Countries and Acute Lower Respiratory Infections in Children. *Thorax* 55: 518-32
114. Smith KR, Shuhua G, Kun H, Daxiong Q. 1993. One Hundred Million Improved Cookstoves in China: How Was it Done? *World Development* 21: 941-61

115. Smith KR, Uma R, Kishore VVN. 2000. Greenhouse Implications of Household Stoves: An Analysis from India. *Annual Review of Energy and the Environment* 25: 741-63
116. Stohl A, Eckhardt S, Forster C, James P, Spichtinger N. 2002. On the Pathways and Timescales of Intercontinental Air Pollution Transport. *Journal of Geophysical Research, in press*
117. Tata Energy Research Institute (TERI). 1998. *Climate Change: Post-Kyoto Perspectives from the South*. New Delhi, India: Tata Energy Research Institute (TERI)
118. U. S. Department of Energy (DOE). 1997. *Renewable Energy Technology Characterization, Topical Report Prepared by DOE Office of Utility Technologies and EPRI, TR-109496*, U. S. Department of Energy (DOE), Washington, DC
119. U. S. Department of Energy (DOE). 2000. *Annual Energy Outlook 2000, DOE/EIA-0383*, Energy Information Administration, Washington, DC
120. von Schirnding Y, Bruce N, Smith KR, Ballard-Tremeer G, Ezzati M, Lvovsky K. 2001. Addressing the Impact of Household Energy and Indoor Air Pollution on the Health of the Poor - Implications for Policy Action and Intervention Measures. In *Working Group 5 (Improving the Health Outcomes of the Poor), Commission on Macroeconomics and Health (http://www.cmhealth.org/wg5.htm)*
121. Wilson R, Spengler JD, eds. 1996. *Particles in Our Air: Concentrations and Health Effects*. Cambridge, MA: Harvard University Press
122. World Bank. 1992. *World Development Report: Development and the Environment*. New York: Oxford University Press
123. World Bank. 2000. *Energy and Development Report 2000: Energy Services for the World's Poor*. Washington, DC: The World Bank
124. World Health Organization (WHO). 2001. *Macroeconomics and Health: Investing in Health for Economic Development. Report of the Commission on Macroeconomics and Health (available online at http://www.cmhealth.org/)*. Geneva: World Health Organization. 202 pp.
125. World Health Organization (WHO). 2002. *World Health Report 2002: Reducing Risks, Promoting Healthy Life*. Geneva: World Health Organization
126. World Resources Institute (with UNEP/UNDP and World Bank). 1999. *World Resources 1998-1999: A Guide to the Global Environment*. New York: Oxford University Press
127. World Resources Institute (with UNEP/UNDP and World Bank). 2001. *World Resources 2000-2001: People and Ecosystems: The Fraying Web of Life*. New York: Oxford University Press
128. Zhang J, Smith KR. 1996. *Indoor Air Pollution: Formaldehyde and Other Carbonyls Emitted from Various Cookstoves*. Presented at The Proceedings of Indoor Air 96: The 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan