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ENERGY MANAGEMENT AND GLOBAL HEALTH*

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■ **Abstract** Energy and energy technologies have a central role in social and economic development at all scales, from household and community to regional and national. Among its welfare effects, energy is closely linked with public health both positively and negatively, the latter through environmental pollution and degradation. We review the current research on how energy use and energy technologies influence public health, emphasizing the risks associated with indoor and ambient air pollution from energy use, and the links between the local and global environmental health impacts of energy use. This review illustrates that, despite their large public health implications, most energy policies and programs in the developing world are fundamentally treated as components of overall economic development, without explicit assessment of their health benefits or hazards. Closer integration of health in energy management can facilitate the development of policies and programs that increase welfare and minimize negative health outcomes. Renewable energy technologies are used as an example of how an integrated energy-health approach can be used in policy analysis and formulation.

CONTENTS

INTRODUCTION

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 (1). Among its various welfare effects, energy is closely linked with public 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 and snails; and water can be disinfected by boiling or by using 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 activities, such as processing of agricultural commodities (e.g., producing refined oil from oil seeds, roasting coffee, and drying and preserving fruits and meats) and production of crafts. The ability to control lighting and heating allows education or economic activities to be shielded from daily or seasonal environmental constraints such as light (Figure 1), temperature, precipitation, or wind. Time and other economic resources spent on collecting and/or transporting fuel can be used for other household needs if energy infrastructure and access is improved. Energy availability for transportation increases access to health and education facilities and allows increased economic

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

activity by facilitating the transportation of goods and services to and from markets. Energy for telecommunications 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. In fact, although the dominant view of development-energy-health linkages has been that improvements in energy and health are outcomes of socioeconomic development (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 (2). 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.

The effects of energy on public welfare and health are also closely related to the source of energy and type of conversion technology utilized (3). Harvesting energy from hydropower and biomass resources can affect the local environment through soil erosion and disruption of the water system or soil nutrient cycle. This may reduce agricultural productivity, limit access to water and energy, change local vegetation, and alter 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 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 (4). Nuclear energy, which does not have combustion byproducts, raises concerns about reactor safety as well as transport and storage of nuclear waste. Therefore, although energy has numerous benefits for social and economic development and public health, the process of energy production can result in short- and long-term negative effects on environmental determinants of health (1, 5–9). We review the current research on how energy use and energy technologies influence public health, with emphasis on the risks associated with indoor and ambient air pollution, which are two important routes for the negative effects of energy use on health (Figure 2). We also consider the links between local and global environmental impacts of energy use.

Currently, approximately 65% of all global primary energy is consumed in the industrialized countries that make up the Organization for Economic Cooperation and Development (OECD) and the former Soviet Union (FSU), with per capita consumption averaging five times that of developing countries (13). Contributions to GHG emissions follow a similar pattern. Per capita energy consumption in North America is more than 25 times that of the poorest nations in sub-Saharan Africa, 20 times the per capita consumption in India, and 10 times that in China (13). Global carbon emissions are approximately one metric ton of carbon per year per person (tC/person-year). 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 they are less than 0.2 tC/year in the 50 developing nations with lowest emissions (14). Coupled with low levels of per capita energy consumption, fuels and energy conversion technologies currently used in developing nations result in much higher exposure to local pollution (15). Therefore, from an environmental health perspective, energy options in developing countries are of notable importance because of lack of access to clean energy sources and technologies. Further, the most rapid future growth in energy consumption is expected to take place in developing countries, as a result of both population growth and economic development (5, 8, 16). This review primarily focuses on developing countries, where much of negative health consequences arising from limited access to clean energy are concentrated. We nonetheless emphasize that many aspects of energy use and its environmental consequences are linked between the developing and industrialized worlds.

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: providing energy for human development and minimizing its negative effects. Throughout the review, we also identify knowledge gaps that should motivate new data collection and research. The next section discusses energy-environment-health linkages, including ambient and indoor air pollution with emphasis on the linkages between household or local and global impacts of energy use. The third section focuses on two important social dimensions of energy and health linkages: poverty and gender. We then use renewable energy technologies as an example of how an integrated energy-health approach may be used in policy analysis and formulations to reduce energy poverty while minimizing the negative consequences of energy use.

THE ENVIRONMENTAL HEALTH IMPLICATIONS OF ENERGY SOURCE AND TECHNOLOGY

This section discusses energy-environment-health linkages, with emphasis on the risks associated with indoor and ambient air pollution, which are two important routes for the negetaive effects of energy use on health (Figure 2). We also consider the linkages between household or local and global impacts of energy use, including global climate change. The ecological effects of energy extraction, 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 but are not reviewed because of the central focus on public health.

Ambient Air Pollution

The burning of oil, coal, natural gas, and biomass results in emissions of 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 exacerbate multiple diseases 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 (17–19). 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 nonetheless been most closely correlated with three species of pollutants in epidemiological studies: fine particulate matter, sulfur dioxide, and tropospheric ozone (18, 20). Toxic chemicals, such as lead and other metals, which are present in some fuels, also have significant health effects (Figure 2).

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 coal and other sulfur-containing fuels). 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 exacerbation are the subjects of ongoing research, there is general agreement that particle size is a strong determinant in its health impact (21). The class of PM below 2.5 microns in aerodynamic diameter ($PM_{2.5}$) is the focus of much health-related inquiry because these small particles can penetrate deep into the lung (18, 20, 22, 23).

The consequences of exposure to high levels of ambient air pollution were observed in the mid-twentieth 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 (24). Subsequent clean air legislation, regulation, and technological advances have reduced ambient air pollution in many cities, especially in higher-income countries.[1] 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 (21, 27). At the same time, the populations of the rapidly expanding megacities 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 twentieth century (18, 28) (Figure 3).

Although urban ambient air pollution has been commonly defined at the level of a city in most epidemiological studies, recent research has illustrated the variation of exposure to this risk and the associated health effects in considerably smaller microenvironments (27, 29–32). This variability occurs because (*a*) the ambient concentrations, composition, and dispersion of pollutants depend on the type and location of pollution source(s) (e.g., use of diesel fuels and mobile or stationary sources), meteorological factors (e.g., wind direction and speed), and urban physical characteristics; (*b*) indoor concentrations in buildings and vehicles as a result of ambient pollution depend on the location, type, and structure of indoor environments; and (*c*) individuals and groups spend various amounts of time in different indoor and outdoor urban microenvironments because of the location of residential neighborhoods and occupational and commercial activities (33). Exposure patterns may also differ by pollutant type. For example, fine particles ($PM_{2.5}$) and ozone tend to be more homogenously distributed over large urban or regional areas than ultrafine particles, nitrogen dioxide and polycyclic aromatic hydrocarbons (PAH), emitted from mobile sources (29).

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[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 (25), although a number of methodological and conceptual questions have been raised about its validity and generalizability (26).

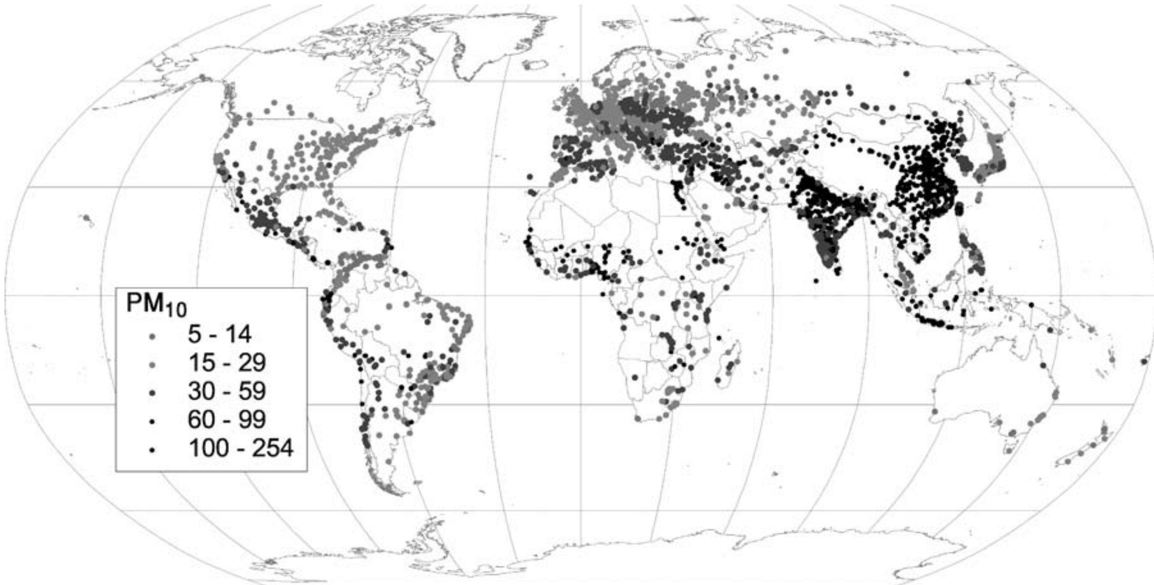

Figure 3 Estimated annual average concentrations of PM_{10} (particulates below 10 microns in aerodynamic diameter) in cities with populations of 100,000 or more and national capitals in 2000. [Figure from (18).]

TABLE 1 Mortality and burden of disease as a result of exposure to ambient air pollution in 2000 (10, 11)

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

[a]Burden of disease is a measure of loss of healthy life caused by premature mortality and morbidity. It is expressed in disability-adjusted life years (DALYs) (12). In the year 2000, there were a total of 1.46 billion DALYs lost in the world from premature mortality and nonfatal health outcomes.

Many of the epidemiological studies on the relationship between ambient air pollution and health, especially studies on effects of long-term exposure, have been conducted at the 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, resulting in significant uncertainty (18). Estimates of global mortality as a result of exposure to ambient urban air pollution are provided in Table 1.

Important research themes that 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 effects on population exposure;
- the health effects of sustained exposure at high concentrations typical of many cities in developing countries; and
- the interactions of ambient air pollution and other risk factors, such as indoor air pollution, smoking, occupational exposures, and nutrition.

Indoor Air Pollution

The relationship between household energy, indoor air pollution, and health has been reviewed in a number of recent works (34, 36, 37, 39, 46). Globally, almost three billion people rely on biomass (wood, charcoal, crop residues, and dung) and coal as their primary source of domestic energy (8, 19) (Figure 4). Biomass

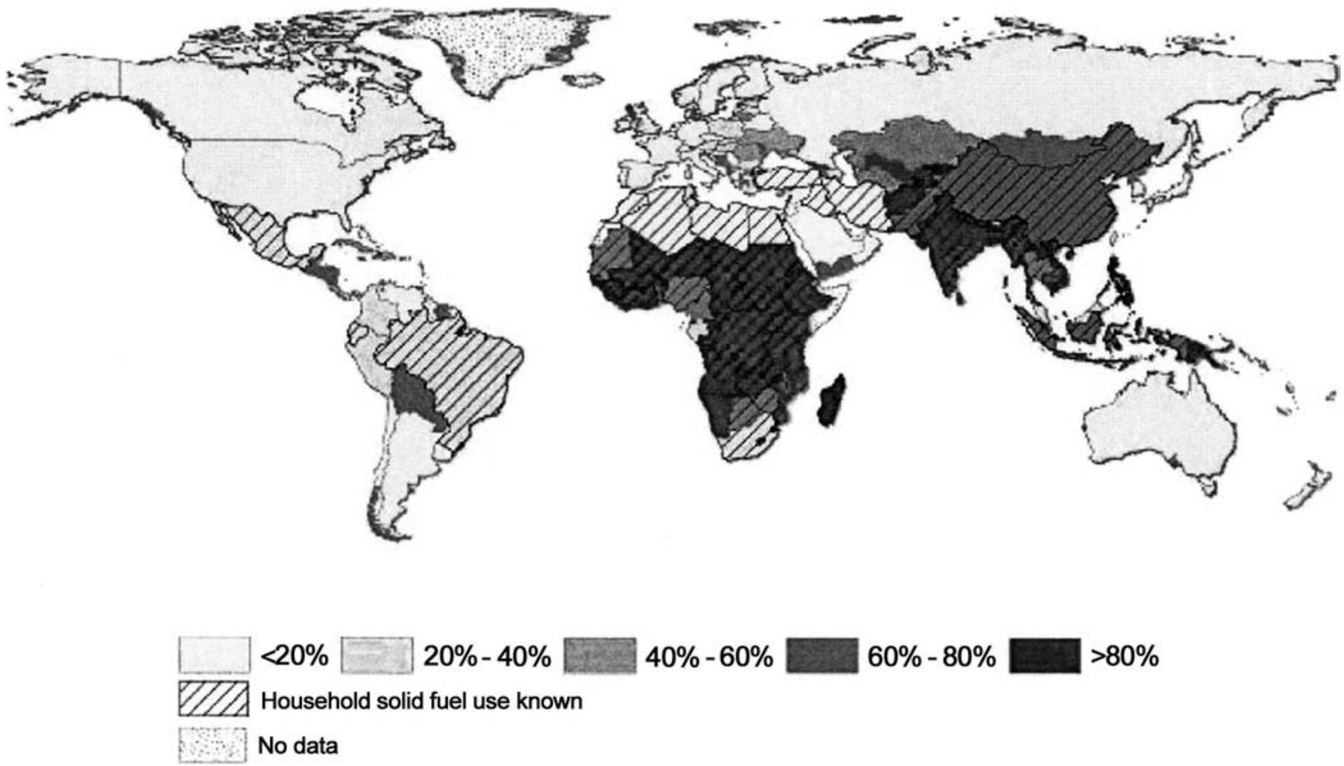

Figure 4 National household solid fuel use estimates in 2000. Solid patterns show the countries for which the household solid fuel use estimates are predictions from a model. [From (39).]

accounts for more than 50% of domestic energy in many developing countries and for as much as 95% in some lower income ones (8, 38).

Hundreds of harmful substances, in the form of gases, liquids (suspended droplets), or solids (suspended particulates), are emitted during the burning of biomass or coal in particularly large quantities when burned in open or poorly ventilated stoves. These pollutants include carbon monoxide (CO), nitrogen dioxide, particles in the respirable range (2 to 10 microns in aerodynamic diameter), and other organic matter (predominantly composed of polycyclic aromatic hydrocarbons and other volatile organic compounds, such as benzene and formaldehyde) (9, 40, 41). Combustion of coal may release oxides of sulfur, arsenic, and fluoride in addition to the above pollutants (42). Monitoring 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 U.S. 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 5000 $\mu g/m^3$ or more throughout the year, depending on the type of fuel, stove, and housing (9, 15, 43–46). It has been estimated that approximately 80% of total global population exposure to airborne particulate matter occurs indoors in developing nations (15, 43).

Exposure to indoor air pollution from the combustion of solid fuels has been implicated, with varying degrees of evidence, as a causal agent of several diseases including acute respiratory infections, chronic obstructive pulmonary disease, lung cancer (from coal smoke), asthma, nasopharyngeal and laryngeal cancer, tuberculosis, low birth weight, and diseases of the eye, such as cataract and blindness (34, 46–48). Most current epidemiological studies on the health effects of indoor air pollution exposure in developing countries have focused on the first three of the above diseases (34, 46). Although detailed epidemiological and toxicological research on the health effects of exposure to indoor smoke from solid fuels has only recently begun, there is increasing consensus of its important role in burden of disease, especially among the poor and marginalized groups. Estimates of global mortality from exposure to indoor solid fuel smoke are shown in Table 2.

As a result of the magnitude of the burden of disease associated with indoor smoke and its unequal global distribution, attention of the research and policy communities has shifted to design and dissemination of interventions (36, 37, 49). The concentrations of different pollutants at locations inside the house depend on energy technology (stove-fuel combination), house design (e.g., the size and construction materials of the house, the arrangement of rooms, and the number of windows) (50, 51), and stove use behavior (e.g., whether fuel is dried before combustion). In addition to pollution levels, exposure depends on time-activity budgets of individual household members (e.g., time spent inside or near the stove and direct participation in cooking tasks) (50, 51). Therefore, reducing exposure to indoor air pollution from solid fuels can be achieved through modifications

TABLE 2 Mortality and burden of disease as a result of exposure to indoor air pollution from solid fuels in 2000 for acute respiratory infections, chronic obstructive pulmonary disease, and lung cancer (10, 11)

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

[a]Burden of disease is a measure of loss of healthy life from premature mortality and morbidity. It is expressed in disability-adjusted life years (DALYs) (12).

in fuel type and energy conversion technology, housing and ventilation, and behavioral factors, such as fuel preparation and individual time-activity budgets (36, 49).

Recent analyses have shown a complex range of energy-environment-behavior interactions in determining exposure to indoor air pollution (36), including whether energy is used for cooking versus heating. Cooking is often done in shorter time intervals and possibly in confined areas, with a subset of household members consistently close to the source of pollution. Further, emissions from open biomass stoves fluctuate over short time intervals, with emission peaks 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 (45, 50) (Figure 5*a*). Because household members who cook—typically females—are closest to the stove at such times, peak emissions contribute significantly to the exposure of female household members (Figure 5*b*) (50). With such exposure patterns, people who cook gain disproportionately small benefits from improved housing ventilation compared to those who are further away from the stove (51, 52). Interventions using cleaner fuels or stoves that reduce peak emissions, on the other hand, would provide comparably larger benefits to female household members (52). Heating, on the other hand, by definition involves longer hours of energy use for a larger area and a relatively similar distance to the energy source for most household members. In contrast to direct inhalation during cooking and heating, bioaccumulation of trace elements (e.g., arsenic and fluorine) in food dried and stored over the stove for long durations is an important route of exposure to these pollutants in parts of China (Figures 6*a*, and 6*b*) (42). In this case, alternative food drying techniques and behavioral change (e.g., washing food before consumption) can reduce exposure and health hazards, such as arsenic poisoning and dental or skeletal fluorosis.

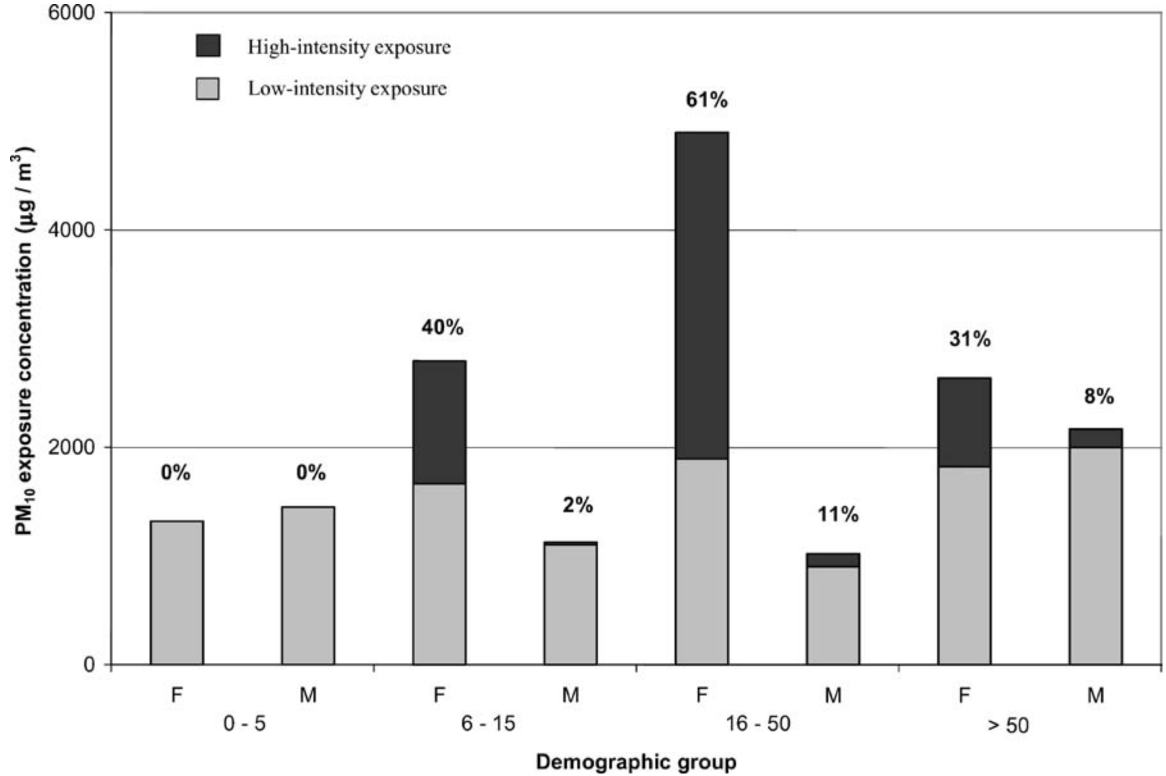

Figure 5*b* For each demographic group the total height of the column is the group's average exposure concentration, divided into average for high- and low-intensity components. The high-intensity component is a result of exposure to peak emissions when household members are close to the stove. [Figure from (50).]

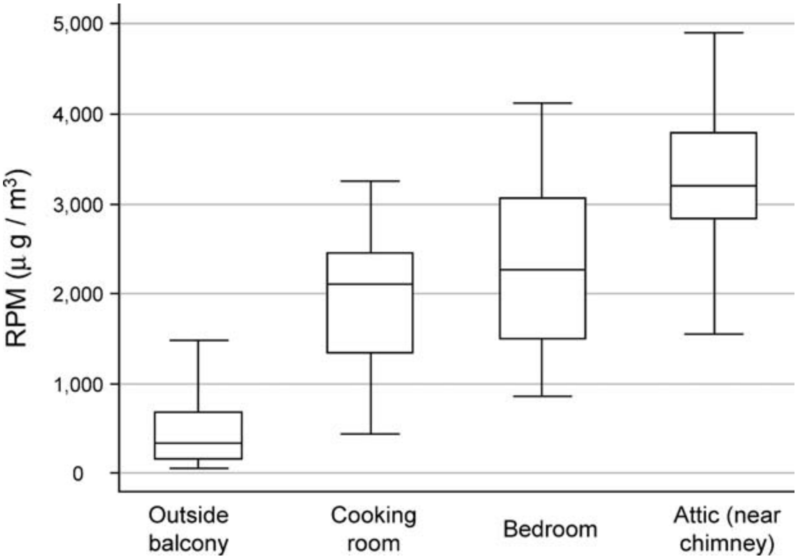

Figure 6*b* Pollution levels are highest near the chimney where food is dried (42). The box plot shows a summary of the distribution of the measurements of respirable particles (RPM) for different households and measurement days. The lower and upper sides of the rectangle show the 25th and 75th percentiles and therefore enclose the middle half of the distribution. The middle line, which divides the rectangle into two, is the median. [Figure from (53).]

To date, most research on indoor air pollution interventions has focused on the energy source with emphasis on improved stoves and fuels, which are believed to provide more affordable options in the near term than a complete shift to nonsolid fuels. Initial improved stove efforts, however, were often marked by a lack of detailed data on stove performance.[2] 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 (44, 57, 58). Beyond technical performance, some of the issues surrounding successful implementation of programs for technology dissemination have been discussed using a limited number of available case studies (49, 58–63). Some important areas for future research include the following:

[2]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 (44, 54–58). 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 (55, 59, 60).

- The relative contributions of energy technology (stove-fuel combination, including multi-stove and multi-fuel scenarios), housing characteristics (such as the size and material of the house, the number of windows, and arrangement of rooms), and behavioral factors (such as the amount of time spent indoors or near the cooking area) affecting exposure. This should also include an assessment of the differential roles of cooking and heating to exposure and their seasonal variations.
- The exposure-response relationship, along a continuum of exposure levels for diseases affected by indoor air pollution. This would allow the health benefits of interventions with partial exposure reduction to be evaluated.
- Longitudinal monitoring of both technical performance of interventions and the socioeconomic and behavioral determinants of their adoption and continued use.

Local-Global Linkages

Air pollution transport on regional to intercontinental scales is emerging as an important component of air quality and health (68). Sophisticated atmospheric models allow estimating the flow of pollution between different countries or regions (69, 70), 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 (71), illustrating the extent of regional impacts even for a single pollutant.

GHGs and pollutants that affect health are both an outcome of processes of incomplete combustion, creating close linkages among the health and global environmental consequences of energy use.[3] A number of works have also considered environmental effects, including GHG emissions, from household energy use in developing countries (72–78). 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 if biomass is burned under ideal combustion conditions, it is effectively GHG neutral.[4] We can therefore identify two critical factors that

[3]Global climate change and the associated shifts in both the mean and variance of meteorological variables, such as temperature and precipitation, will undoubtedly affect public health in many societies and geographical areas (4). 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 timescales due to economic and demographic development and technological innovation (64–67).

[4]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.

affect the extent of GHG emissions from biomass energy: the sustainability of the biomass harvest and the mode 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 welfare of those households that rely on biomass for their energy purposes, as discussed elsewhere (54, 73, 75, 76, 79). 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 (1, 9). Although CO_2 is the most commonly discussed GHG, particularly in fossil-fuel-based systems, it is the non-CO_2 GHGs 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 (80). These non-CO_2 GHGs (e.g., methane) have a greater warming effect than CO_2 on a molar basis (81).

Emissions of GHGs for a number of developing country household energy technologies (stove-fuel combinations) have been calculated using measurements or estimates of various pollutants (CO_2, methane, CO, and nonmethane hydrocarbons), with examples presented in Figure 8. In Figure 8, the height of each bar shows the average emissions of each pollutant per unit of energy. The lines show the sum of non-CO_2 GHGs (squares) and sum of 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, whereas 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. As seen in Figure 8, both liquified petroleum gas (LPG) and kerosene have energy-based emissions that are comparable to, if not lower than, the emissions from renewable biofuels, and these emmissions are far lower than the emissions from biofuels when they are not used renewably. This result implies that, given current combustion technology and user behavior, a shift to kerosene and LPG can reduce exposure to indoor air pollution without additional GHG emissions (82). Significant increase in the usage of kerosene and LPG as interventions for reducing the health hazards of indoor air pollution would, however, necessitate considerably larger supplies than are currently accessible by most developing countries and an infrastructure for their delivery (see also Table 3).

The linkages between exposure to air pollution at household and community levels on the one hand and global environmental impacts of energy use on the other may provide an opportunity to simultaneously address multiple energy-environment-health issues (83) (Appendix 1). At the same time, given the lower historical and current per capita emissions of GHGs 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 from increased energy used in developing countries (84).

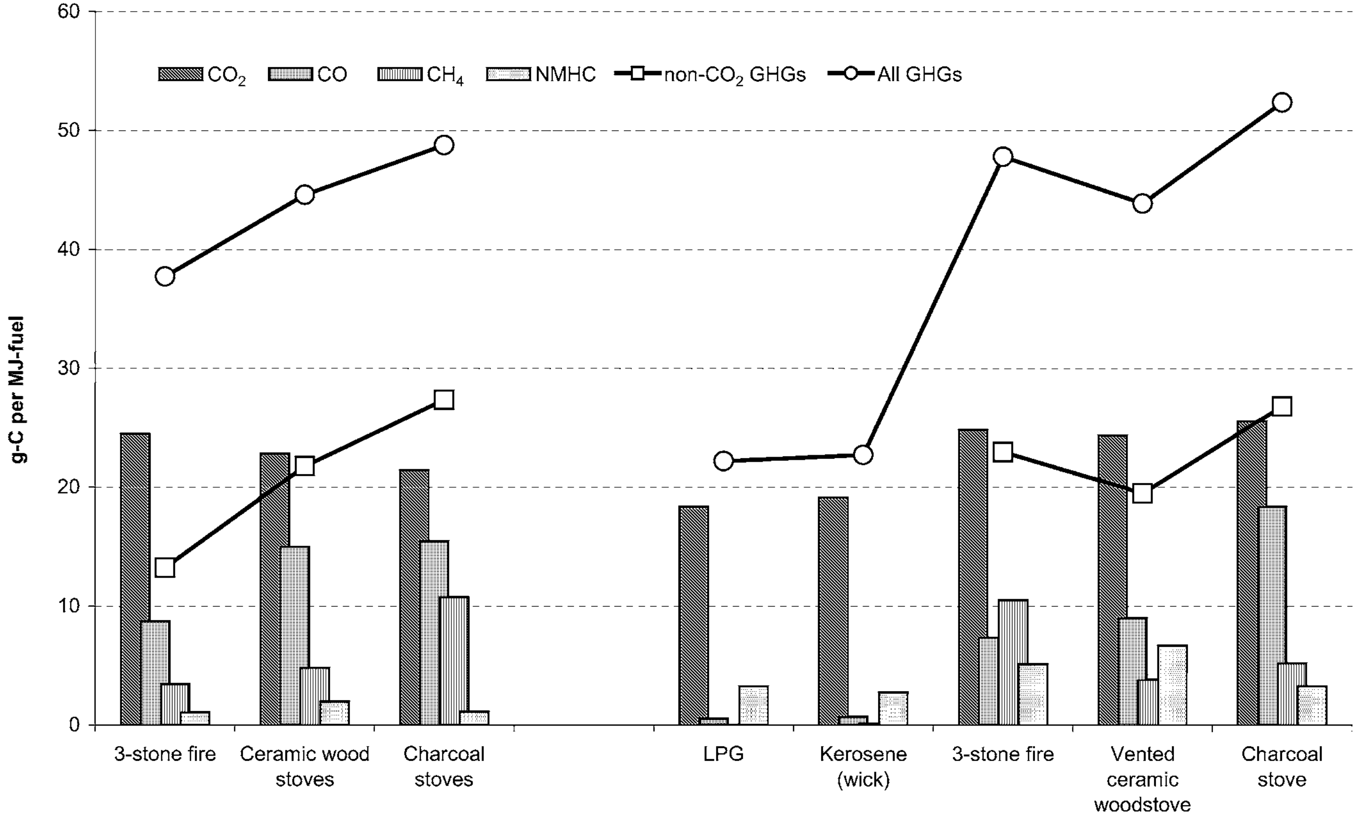

Figure 8 Comparison of energy-based emission factors (weighted by 20-year global warming potential) by stove-fuel category for India and Kenya. The first three stoves (*left*) are estimates from Kenya (78), and the last five (*right*) are estimates from India (77). All biomass stoves used acacia wood or charcoal made from acacia in these measurements. LPG is liquified petroleum gas.

TABLE 3 Household energy choices and barriers [adapted from (94, 102)]

	Selected determinants of adoption		
Energy source	**Equipment costs**	**Nature of payments**	**Nature of Access**[a]
Electricity	Very high	Lump sum	Restricted
Bottled gas (liquified petroleum gas, butane, natural gas)	High	Lump sum	Often restricted; bulky and specialized 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 cost where residues are used as fodder and/or dung is used as fertilizer

[a]Nature of access refers to ease with which households can choose the fuel if they are willing to pay for it and is determined by physical and institutional infrastructure.

Further, the complex development-energy-environment-health interactions often require more integrated policy analysis than a simple double-dividend approach, including joint implementation of multiple policies (Appendix 2).

SOCIAL DIMENSIONS OF ENERGY-HEALTH LINKAGES

Energy and health both have complex socioeconomic determinants. This section focuses on two important social dimensions of energy and health linkages: poverty and gender. Although considered in separate sections, poverty, gender, and resource use are also interrelated, and women in households of differing socioeconomic status experience the health and welfare implications of energy and energy technology in different forms (85).

Energy, Poverty, and Health

Although the poor in industrialized nations spend a larger fraction of household budget on energy, the poverty-energy links are strongest in low-income countries.

It is well-known that poor households in developing countries have limited access to clean and secure sources of energy, owing to lack of resources and infrastructure (86). For example, in a participatory poverty assessment in South Africa, which aimed to provide an understanding of poverty from the perspective of those who experience it, limited access to clean energy and energy insecurity were identified as indicators of poverty and ill-being by the poor themselves (87).

Figure 9 shows the fraction of households using solid fuels among those living on less than 1 dollar ($) per day, between $1 and $2, and greater than $2 per day in various regions. As seen, except in the two (sub-Saharan) African regions, 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.[5] The poor are also likely to live in parts of cities that are more affected by urban ambient air pollution, such as near highways and industrial sites (88–91). 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 mean that the health consequences of energy are often disproportionately greater on the poor than those in higher income strata (92).

The correlation between poverty and energy source (i.e., fuel) has been considered in a number of works, often formalized in the energy ladder framework (8, 16, 63, 94). The energy ladder framework hypothesizes that households switch to cleaner sources of energy with increasing income. Since the formulation of this framework, a number of works have confirmed this hypothesis but have illustrated that use of multiple fuels is common across income levels (95, 96). More broadly, although the energy ladder is a convenient qualitative representation of the correlation between household energy supply and household socioeconomic 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, the energy ladder framework would imply a deterministic view of economic development and energy that need not hold if the circumstances—including the cultural context, policy, and infrastructure—are different from those of the original formulation. This deterministic formulation can also hinder innovative technological and policy approaches to addressing the energy issues of the poor that bypass the energy ladder. The energy ladder construct is also 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.[6]

[5]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.

[6]Empirical examples of the importance of technology access and uncertainty can be found in the experience of diffusion of agricultural technologies (97–101). Because the outcome of technology is different (crop production versus energy consumption and health), the results may not be directly transferable to energy technologies.

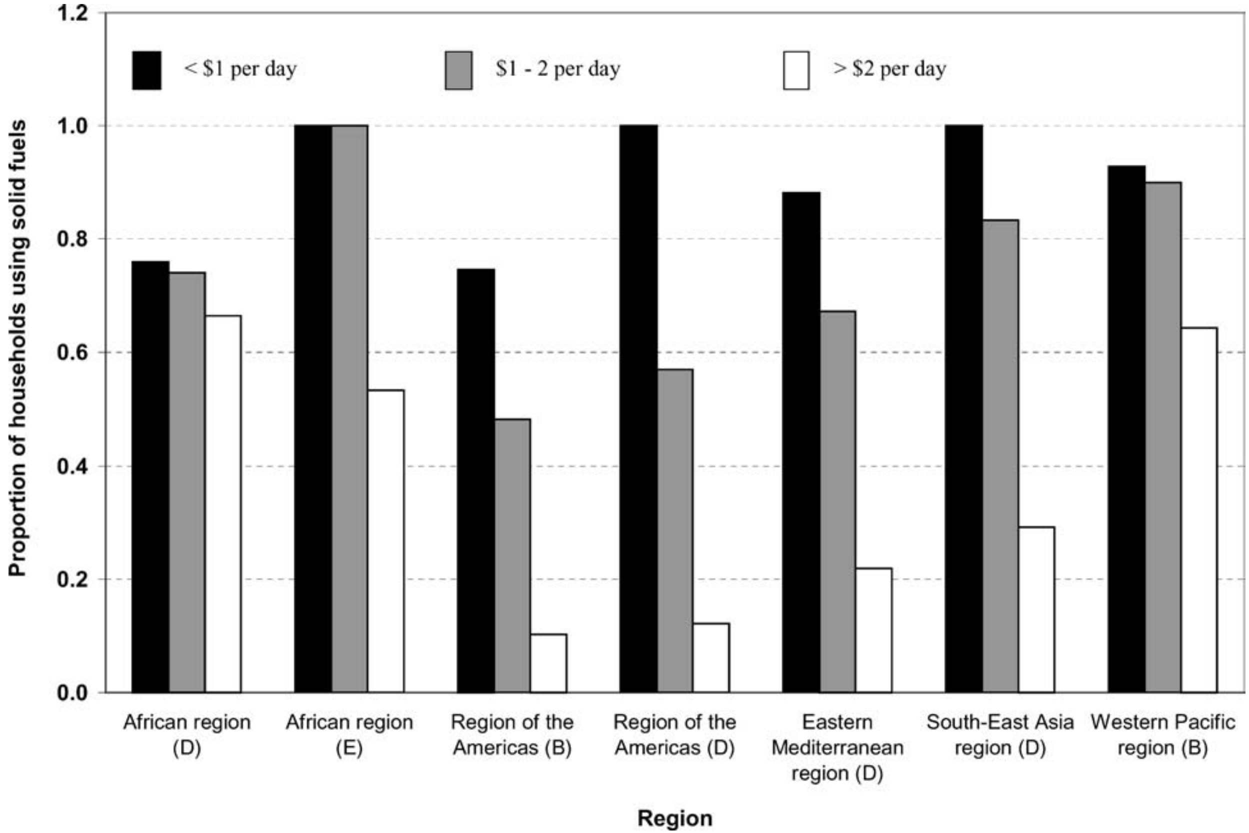

Figure 9 Decreasing prevalence of solid fuel use with increasing household income (93). The regions are the World Health Organization regions divided by their levels of child and adult mortality: B, low child mortality and low adult mortality; D, high child mortality and high adult mortality; and E, high child mortality and very high adult mortality.

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 source of additional freedom to choose certain types and quantities of fuel or the technology for fuel utilization. What the household actually does with the extra income will be decided by 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 of other factors (Table 3) (94, 102). Households may spend extra income on nonenergy 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).

Energy, Gender, and Health

International development research and policy have considered intrahousehold allocations of resources in addition to household level welfare effects. Energy is the aspect of development in which gender differentials in access to resources and its consequences are possibly most observable (see Reference 103 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, women allocate 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 kg of wood, the burden of work falls disproportionately on women, who may expend a significant fraction of their daily caloric needs gathering fuel (Figure 10) (104). 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 (105).

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 (36, 51, 106), including respiratory or eye diseases from 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 2) were among women (10, 11).

Increased access to clean energy sources can improve the day-to-day as well as long-term welfare of female household members. Health improvements, 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 Reference 8 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 inter- and intrahousehold economic and social institutions 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 (54, 79). 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 (107). Further, access to these opportunities can be sustained only if coupled with increased female participation in the social decision making and policy process (108, 109).

ENERGY MANAGEMENT AND PUBLIC HEALTH

Technology Options

Conventional energy sources based on oil, coal, and natural gas have proven to be highly effective drivers of economic development but at the same time damaging to the environment and to human health as described above (3). Over decades of development aid and lending, bilateral and multilateral development agencies have financed numerous conventional fossil-fuel-based energy projects and large-scale hydroelectric power in developing countries, which resulted in large burden of debts, had significant impacts on local environment and health, and provided only a small fraction of population with adequate energy services (110). The use of fossil-fuel-based energy as the sole or main driver of development appears increasingly problematic for many reasons, including uncertainty in price and reliability of international energy markets as well as their environmental and health consequences (see Reference 3 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, is enormous. Renewable energy sources, such as biomass,[7] wind, solar, hydropower, and geothermal, can provide sustainable energy services, using a mix of readily available, indigenous resources with potential to result in minimal local environmental damage or net emissions of

[7]In this context, biomass energy can be distinguished from traditional household biomass use in developing countries, described above. In these applications solid biomass feedstock is either burned in high-efficiency combustion devices so that potentially harmful combustion emissions can be minimized, or it is converted to a more convenient and cleaner energy carrier, such as solid briquettes or pellets, liquid or gaseous fuels, or electricity before final consumption.

GHGs. A transition to renewables-based energy systems looks increasingly desirable and possible because 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 continues to fluctuate. If social and environmental costs are included in the estimation of electricity costs, RETs become still more attractive (111–113).

Renewable energy systems are usually implemented in a small-scale decentralized model that is inherently conducive to, rather than at odds with, many welfare and public health goals of energy distribution. These systems can have dramatically reduced as well as spatially dispersed environmental impacts, compared to larger and more localized effects of conventional energy sources, such as local ambient air pollution, acid rain, and ecological degradation. Although evaluation of RETs is currently on the basis of 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 (17). 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% of the global electricity supply provided by this source. New renewable energy sources (solar energy, wind energy, modern bioenergy, geothermal energy, and small hydropower) are currently contributing about two percent of the global energy mix. In developing nations, RETs 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 to 100 watt peak (Wp)] solar photovoltaic systems have been commercially financed and installed in homes, battery charging stations, and other small enterprises (115); a government program in Mexico has disseminated over 40,000 such systems; and in the Inner Mongolia autonomous region of China over 130,000 small-scale windmills provide electricity to about one third of the nongrid-connected households in this region (116, 117). 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 RET systems. This strategy can also reduce the need for the construction of large power grids, further mitigating the environmental and health costs of electrification.

Policy Instruments

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

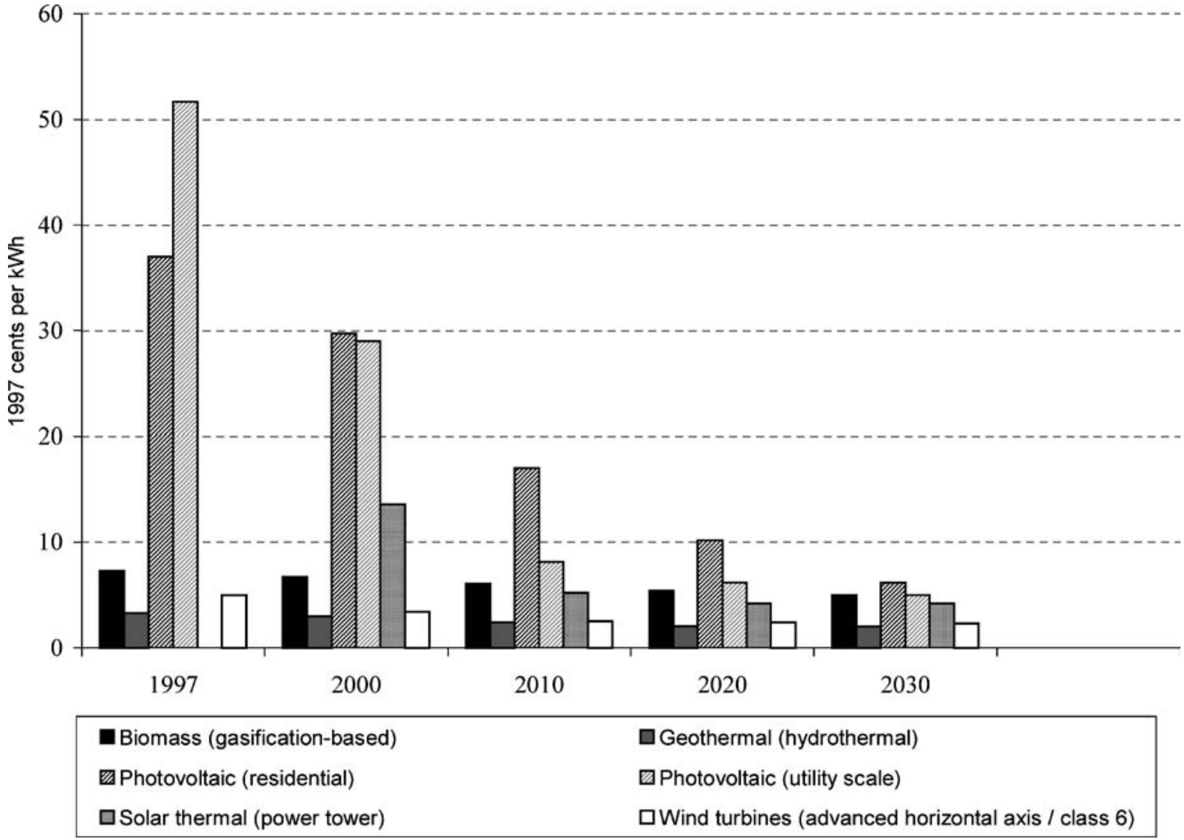

Figure 11 Levelized cost of electricity forecast for renewable energy technologies (112, 114). Levelized costs account for capital costs, operation, and maintenance.

the twenty-first century their contribution might range from the present figure of nearly 20% to more than 50%. In essence, however, RETs face a situation similar to one 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 will only be realized if energy projects and policies are evaluated and implemented based on their overall social, economic, environmental, and public health merits. See References 102 and 112 for more detailed discussion.

The economic and policy mechanisms needed to support the widespread dissemination of 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.[8]

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. 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. At the same time, 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 low-cost delivery of coal to power plants, and a wide range of other subsidies.

RETs tend to be characterized by relatively low environmental costs. Many of these environmental costs are, however, externalities that are not priced in the market. 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 (Appendixes 1 and 2).

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

INVESTMENT IN INNOVATION Recent efforts targeting a variety of small-scale traditional, fossil-fuel and RETs 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 renewable energy sources, improved efficiency cookstoves, photovoltaic solar home systems, wind turbines for household and microenterprise applications, microhydro generators, and advanced biomass energy systems. Some of these technologies have already had a significant impact on local patterns of energy use, economic activity, and the environment (118). 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 (119, 120). There is also a systematic lack of microcredit 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. 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. Finally, all too often projects are planned, implemented, or evaluated on the basis of unexamined assumptions about local conditions and the social and economic consequences of the project (61).

Research and development (R&D) requires long-term commitment because the timescale 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 seem largely a luxury, rarely supported against the other and often more apparently pressing needs of energy development. As seen with similar experiences in agriculture and in health, local R&D is crucial to technology development and dissemination.

CONCLUSIONS

We have described some of the linkages between public health and energy. In spite of 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, such as those discussed for RETs, that increase welfare and minimize the negative health consequences that those activities might entail (121).

In particular, the neglect of energy R&D capacity to meet global and national energy needs without significant public health consequences 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 R&D capacity by industrialized nations (122). The commitments made during the World Summit on Sustainable Development in Johannesburg should provide a critical opportunity to bring attention to this underinvestment and to build a full understanding of the need and importance of energy R&D and its public health implications.

ACKNOWLEDGMENT

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APPENDIX 1

Integrated Environmental Strategies for Air Pollution and GHG Reduction 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 were estimated for specific interventions.

For the first analysis, a moderate climate policy scenario was considered. This scenario has been developed for the Chilean National Environmental Commission, and it considered only nonpositive costs measures, such as 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, resuspended dust and PM_{10}) were estimated from emission factors recommended by the Intergovernmental Panel on Climate Change. 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 different cities taking into consideration local demographic and economic data.

The Santiago estimates were made on the basis of local epidemiological studies and 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 U.S. values (mainly for willingness-to-pay 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 1800 [95% confidence interval (CI) 1200–2300] for NO_X; 3000 (95% CI 2100–3900) for SO_2; 31,900 (95% CI 21,900–41,900) for PM; and 630 (430–830) for resuspended 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 calculated on the relative contribution of unit pollutant emissions to ambient concentrations during Santiago's winter). As seen in the figure, most measures have a bigger local air pollution reduction than carbon reduction. Two measures [conversion of existing diesel buses (EPA 91) to compressed natural gas (CNG) and extended life span of existing diesel buses] have zero or negative air pollution reductions, whereas 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$/tCe (tons of carbon equivalent) were considered for valuing the carbon reductions, whereas the previously described values were considered for local air pollutant reductions. A comparison of the benefits shows that health benefits are generally larger than carbon benefits. For the fuel switching measures, carbon benefits were estimated as 9% to 28% of the health benefits (the latter figure for the 50 US$/tCe case for diesel to natural gas switch in boilers). In the transportation sector, the ratio was estimated from 0% 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

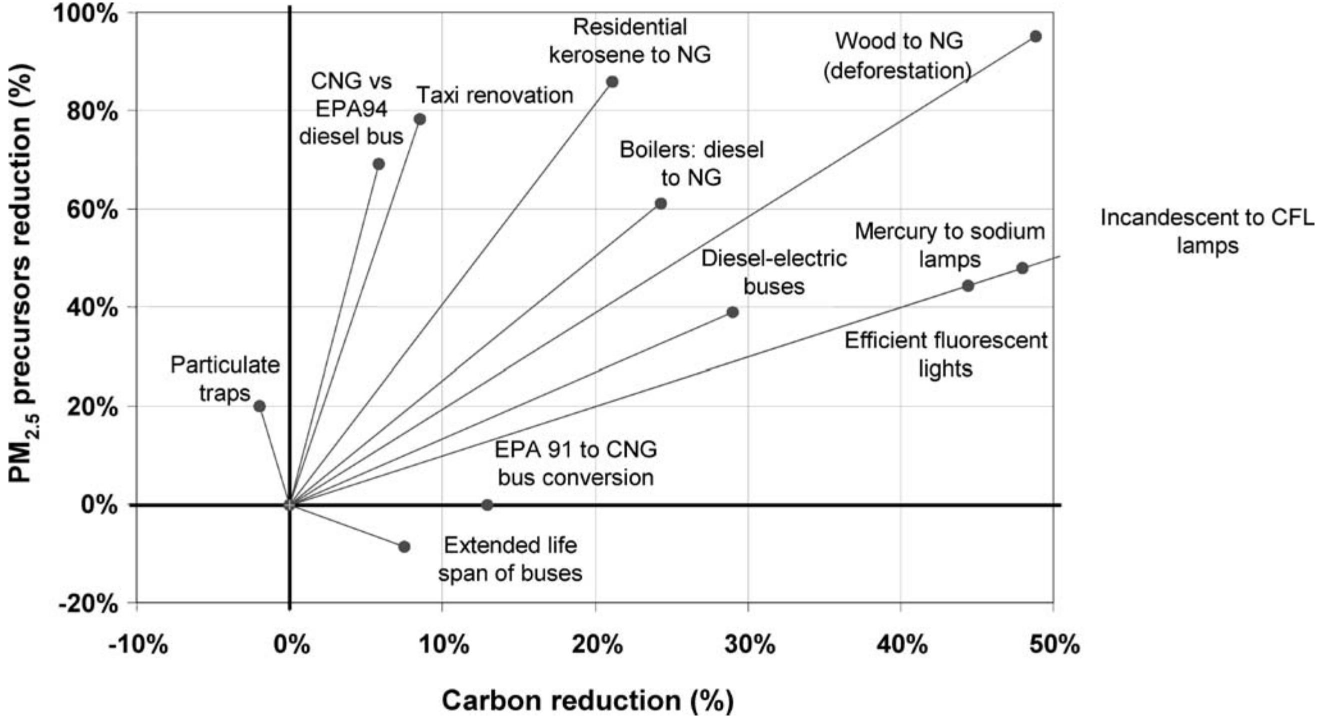

Figure 12 Percentage reductions in CO_2 equivalent and in local air pollutants for selected interventions in Santiago, Chile. The intervention incandescent to CFL lamps is on the same line as mercury to sodium lamps with a CO_2 reduction of about 80% (i.e., outside the scale of current figure). Abbreviations are CNG, compressed natural gas; CFL, compact fluorescent lights; and NG, natural gas. EPA 91 and EPA 94 are emission standards set by the U.S. Environmental Protection Agency (EPA).

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 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.

APPENDIX 2

Integrating Energy, Environment, and Public Health Policies: Charcoal in Kenya

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 multiple pollutants (123–125).

Although GHG emissions from charcoal production and end use are much higher 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 PM_{10} exposure by 75% to 95% on average for different demographic groups resulting in a 21% to 44% decrease in childhood acute lower respiratory infections as well as significant adult health benefits (52).

FUEL SWITCHING AND CHARCOAL MARKETS Nations like Kenya, which contribute very little to the total global release of GHGs (much less than 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. This is particularly important with the increasing realization of the central role of health in meeting the development goals of poor nations (126). 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 (127). In Kenya for example, over 80% of the urban population, some 1.4 million households, use charcoal as their primary cooking fuel (128). 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, such as 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 is 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 References 29 and 130 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 enforced. Despite these barriers, tens of thousands of people make their living by participating in one or more aspects of the charcoal supply chain, and revenues from the charcoal trade are thought to exceed US$300 million (131).

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 from charcoal 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, ensure sustainable levels and methods (74) of production are maintained, and ensure 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 Although 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-emission) charcoal stoves, which reduce emissions by improving combustion efficiency. Also, users generally see substantial fuel savings. Such charcoal stoves have been widely disseminated and adopted in urban Kenya, for example, although they are still short of saturation levels and offer potential for wider dissemination in rural areas (62). 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 substandard stoves have crept into the market since donors and nongovernmental groups have stopped participating in stove design and dissemination projects (132).

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 GHG emissions reduction activities.

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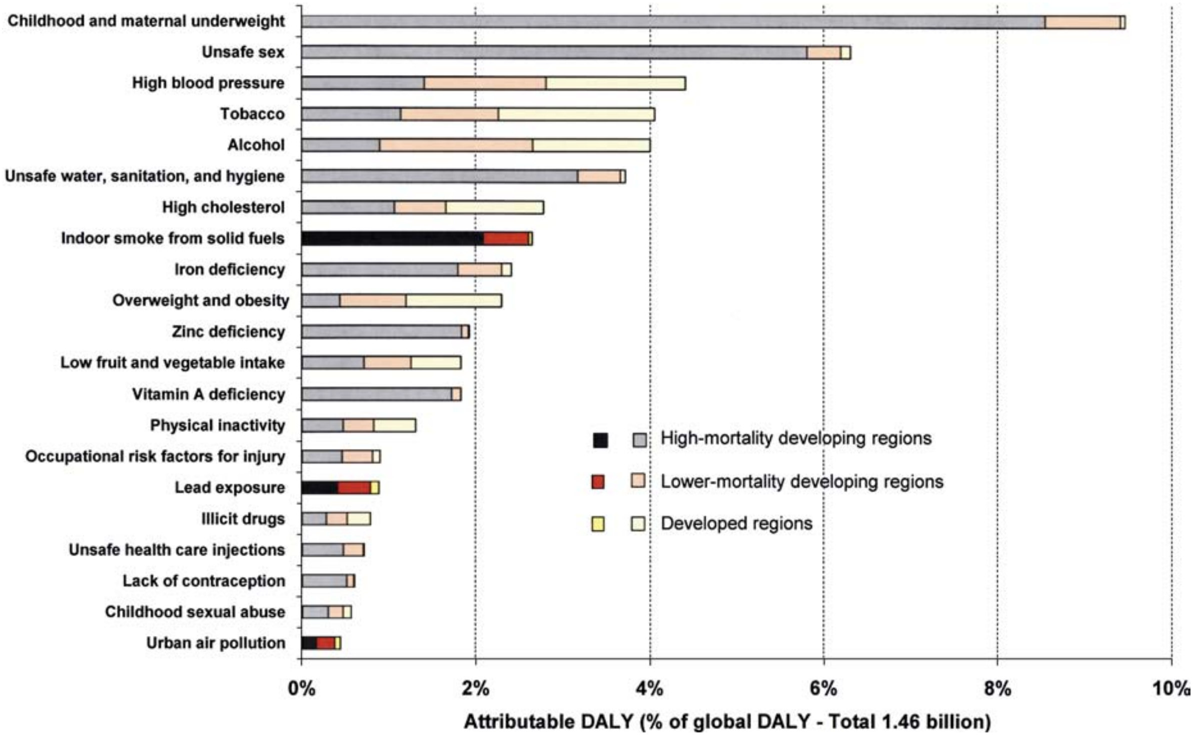

Figure 2 Burden of disease for some of the direct effects of energy systems (highlighted in black, red, and yellow) relative to other major global risk factors [see (10, 11) for a description of methods]. Burden of disease is a measure of loss of healthy life due to premature mortality and morbidity. It is expressed in disability-adjusted life years (DALYs), an aggregate measure of loss of life to premature mortality and time lived with nonfatal health outcomes (12). In the year 2000, there were a total of 1.46 billion DALYs lost in the world from premature mortality and nonfatal health outcomes.

Figure 5*a* In central Kenya, household members who cook are exposed to episodes of high pollution when they work directly above the fire. [Photograph by M. Ezzati, from (50).]

Figure 6*a* An important route of exposure to fluorine and arsenic from stove use in southern China is bioaccumulation in food (corn and chili), dried near a chimney. (Photograph by J. Arnold, China.)

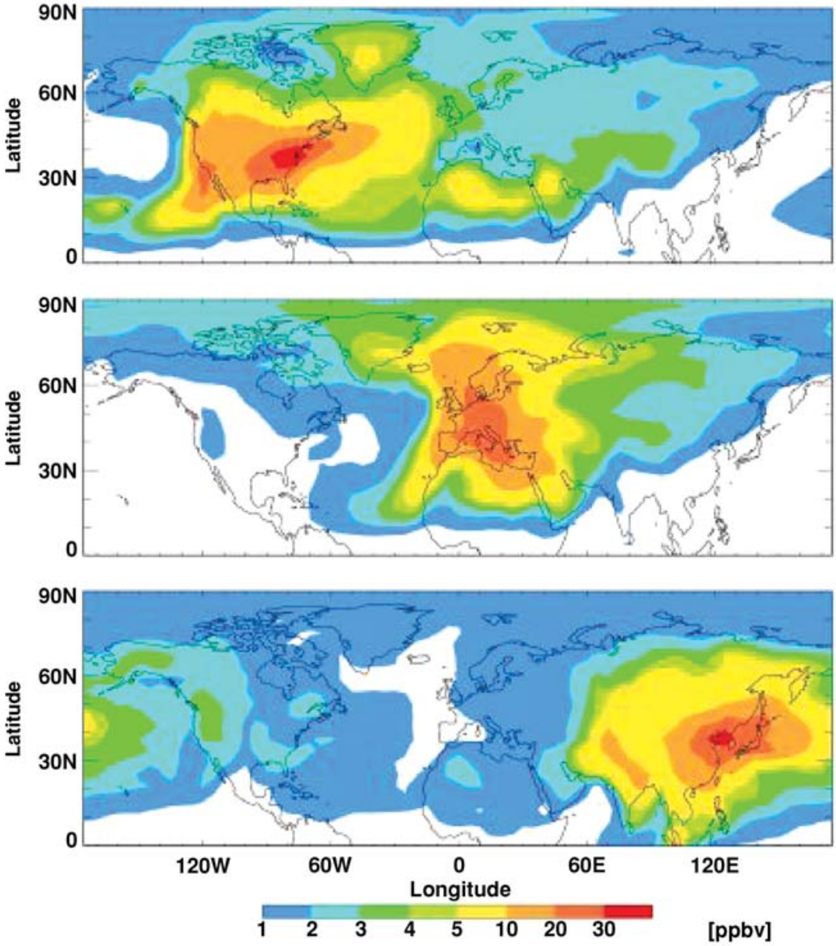

Figure 7 Model estimates of surface ozone attributable to anthropogenic emissions from North America (*top panel*), Europe (*middle panel*), and Asia (*lower panel*) during June, July, and August 1997. Units are in parts per billion volume (ppbv). [From (71).]

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