HOUSEHOLD USE OF SOLID FUELS

1. Exposure Data

1.1 Description and determinants of use of household fuels

1.1.1 *Introduction*

All over the developing world, meals are cooked and homes are treated with home-made traditional stoves or open fires. These stoves are fired with either biomass fuels, such as wood, branches, twigs or dung, or coal. When these are not available, agricultural residues or even leaves and grass are used. The smoke emitted from such stoves is made up of particles and gaseous chemicals. It is estimated that as many as 70% of households in developing countries use fuels such as wood, dung and crop residues for cooking (International Energy Agency, 2002; WHO, 2006). The seemingly 'free' availability of biomass fuels from nature makes them the primary fuel source for household purposes.

The problems related to the use of biomass as an energy source have been an issue of concern for more than three decades. The traditional stoves commonly used for burning biomass energy have long been found to be highly inefficient and to emit copious quantities of smoke due to the incomplete combustion of fuels. This inefficiency has also had consequences on the environment, since intense collection of fuelwood has resulted in deforestation in highly populated areas. The use of such fuels has also adversely affected health. In addition, the cost involved in terms of human energy and time required to collect and process such fuel has serious implications for productivity and gender equity.

Attempts to convert households from these fuels to modern fuels or from traditional stoves to more efficient and cleaner burning stoves through reform of the energy sector or indigenous innovative technology have been very effective in some countries, but dismal or non-existent in others. This section provides a description of the various fuels and some background on their energy content and the efficiency of their use. Thereafter, the current trends and the known determinants that explain the widespread use of biomass fuels and coal are reviewed. Since indoor air pollution from the use of biomass and coal in the domestic sector is largely a phenomenon of the developing world, emphasis is mainly on these countries.

1.1.2 *Description of household fuels*

(a) *Types of solid fuel*

A wide variety of fuels are used in households in developing countries for cooking and heating. Solid fuels refer to both biomass fuels and coal. The most common fuel used for cooking and heating is wood, followed by other solid biomass fuels, such as charcoal, dung, agricultural residues and sometimes even leaves and grass. These fuels are often collected from the local environment in rural areas and are purchased through markets in urban areas.

In some rural areas, farmers who own or manage livestock have the option of using a digester to turn dung and agricultural waste into biogas, which is a fuel that can be used for both heating and/or lighting. Electricity is not commonly used in developing countries for cooking, but is often used for other purposes, such as lighting and powering appliances. In China and some coal-producing regions in India and South Africa, coal is used as a cooking and heating fuel, sometimes in combination with other biomass fuels. Raw coal may be used in many forms from lumps to briquettes to fine powders. Coal may be processed as simply as forming coal balls or cakes by hand followed by sun-drying, or may undergo a sophisticated procedure, such as being blended into a uniform mixture with binders to reduce sulfur and particulate emissions and formed into briquettes designed to burn efficiently and cleanly in special stoves.

Modern fuels include liquefied petroleum gas (LPG), kerosene and electricity.

(b) *Energy density and efficiency of fuels*

Fuels differ in their energy densities and efficiency (Table 1.1). Modern fuels such as LPG have the highest energy content per kilogram of fuel at approximately 45 MJ/kg. In contrast, crop residues and dung have energy densities of about 14 MJ/kg of fuel. The efficiency of a fuel is measured by the amount of energy used for cooking compared with that which escapes from the stove without actually heating the food. The efficiency of cooking with LPG is estimated to be approximately 60% compared with only 12% for agricultural residues burnt in traditional stoves. This is one of the reasons that commercial fuels such as LPG are considered to be superior to crop residue and dung (see below). Coal is a highly variable fuel, and ranges from anthracite with a high heating value anthracite through various forms of bituminous coal to lignite and peat. Each of these types of coal can contain different levels of moisture, non-combustible inorganic material (ash), sulfur and sometimes significant levels of other impurities, such as arsenic, fluorine, lead and mercury.

All fuels are burned in various types of device to provide the heat necessary for cooking. The device can be relatively efficient or inefficient and be associated with high or low levels of pollution. As indicated in Table 1.1, conversion efficiencies for kerosene stoves range from 35% for wick stoves to 55% for pressure stoves; those for fuelwood stoves range from 15% for traditional stoves to 25% for improved stoves. Improved stoves have the potential to reduce indoor air pollution levels, to burn wood or other biomass more efficiently and sometimes to reduce average cooking times.

Table 1.1. Typical efficiencies at the final consumption stage of cooking

Fuel source	Energy content (MJ/kg)	Typical conversion efficiency[a] (%)	Useful energy at final consumption stage of cooking (MJ/kg)	Approximate quantity of fuel necessary to provide 5 GJ of useful energy for cooking (kg)
Liquefied petroleum gas	45.5	60	27.3	180
Natural gas	38 [MJ/m^3]	60		219 [m^3]
Kerosene (pressure)	43.0	55	23.6	210
Kerosene (wick)	43.0	35	15.1	330
Biogas (60% methane)	22.8 [MJ/m^3]	60		365 [m^3]
Charcoal (efficient stoves)	30.0	30	9.0	550
Charcoal (traditional stoves)	30.0	20	6.0	830
Bituminous coal	22.5	25	5.6	880
Fuelwood (efficient stoves), 15% moisture	16.0	25	4.0	1250
Fuelwood (traditional stoves), 15% moisture	16.0	15	2.4	2000
Crop residue (straw, leaves, grass), 5% moisture	13.5	12	1.6	3000
Dung, 15% moisture	14.5	12	1.7	2900

From Sullivan & Barnes (2006)

[a] The typical conversion efficiency for charcoal, fuelwood and kerosene is based on their respective stove types.

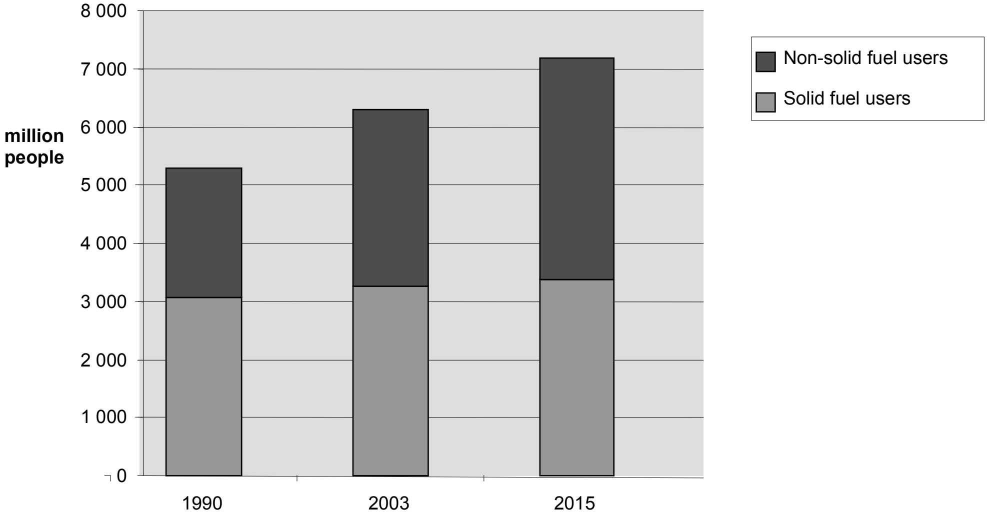
1.1.3 *Use of solid fuels worldwide*

Biomass is often the primary source of household energy in developing countries. Just over three billion people use biomass fuels for cooking and heating in developing countries and approximately 800 million people, mostly in China, use coal. As indicated in Figure 1.1, these statistics have been relatively stable over the last 15–20 years and are expected to continue into the future (WHO, 2006). Thus, it is anticipated that the use of solid fuels and especially biomass fuels will persist for many years to come.

Significant regional variations occur as well as differences between urban and rural areas. The findings that have been collected from national surveys conducted by the

Demographic and Health Surveys (DHS), the World Bank's Livings Standards Measurement Study (LSMS) and other similar studies are presented in Table 1.2. The estimates in Figure 1.2 are averages of main fuel use across the set of countries found in Table 1.2.

Figure 1.1. Population using solid fuels (millions) in 1990, 2003 (mid-point) and 2015



Adapted from WHO (2006) (Figure 14: Trends in solid fuel use)
Data for 2015 are based on:

- a business-as-usual scenario that applies the observed annual increase in the number of people with access to cleaner fuels from 1990 to 2003 to the period 2003–15;
- the voluntary Millennium Development Goal target proposed by the UN Millennium Project to halve the number of people without access to modern cooking fuels between 1990 and 2015.

Table 1.2. Household use of main cooking fuels in selected developing countries, national household surveys 1996–2003

Countries	% Solid fuels[a]			% Modern fuels[a]			Data[b]	
	Rural	Urban	National	Rural	Urban	National	Source	Year
AFRICA								
Benin	98.7	87.5	94.6	1.3	12.5	5.4	DHS	2001
Burundi	99.9	98.1	99.8	0.2	1.9	0.2	EP	1998
Cameroon	98.2	62.2	82.8	1.8	37.8	17.3	ECAM	2001
Eritrea	97.4	30.4	79.7	2.6	69.6	20.3	DHS	1995
Ethiopia	99.9	72.9	95.4	0.1	27.1	4.6	DHS	2000
Ghana	99.4	88.0	95.8	0.6	12.0	4.2	CWIQ	1997
Kenya	94.7	33.8	81.8	5.1	66.1	18.1	CWIQ	1997
Madagascar	98.8	96.2	98.2	1.1	3.7	1.7	EP	1999

Table 1.2. (contd)

Countries	% Solid fuels[a]			% Modern fuels[a]			Data[b]	
	Rural	Urban	National	Rural	Urban	National	Source	Year
AFRICA (contd)								
Malawi	99.6	83.0	97.4	0.4	17.0	2.6	DHS	2000
Mali	99.8	98.4	97.9	0.2	1.6	0.4	DHS	2001
Niger	98.4	94.8	97.8	1.6	5.2	2.2	EPCES	1995
Nigeria (eight states)	94.2	57.4	85.7	5.9	42.6	14.0	CWIQ	2002
Rwanda	99.9	98.1	99.8	0.1	1.9	0.2	DHS	2000
Uganda	98.7	85.0	96.8	1.3	15.0	3.2	DHS	2001
Zambia	98.1	62.4	85.9	1.9	37.6	14.1	DHS	2001
Zimbabwe	93.6	4.7	59.7	6.4	95.3	40.3	DHS	1999
LATIN AMERICA								
Bolivia	80.4	7.1	34.4	19.6	92.9	65.6	DHS	1998
Brazil	38.3	2.7	9.3	61.7	97.3	90.7	PNAD	1999
Chile								
Colombia	48.2	3.4	19.5	51.8	96.6	80.5	ENH	2000
Costa Rica	23.9	3.6	11.8	76.1	96.4	88.2	EHPM	2000
El Salvador	71.7	17.6	37.9	28.3	82.4	62.1	EHPM	2000
Mexico								
Paraguay	71.3	22.0	43.3	28.7	78.0	56.7	EPH	2000
Uruguay	1.8	0.4	1.1	98.2	99.6	98.9	ECH	2000
Haiti	99.6	91.0	96.4	0.4	9.0	3.6	DHS	2000
Nicaragua	93.3	46.1	64.4	6.8	53.9	35.6	LSMS	2001
ASIA								
India	90.2	29.2	73.7	8.5	66.3	24.3	NSS	2000
Nepal	95.6	39.9	89.7	4.4	60.1	10.3	DHS	2001
Pakistan	95	28	76	5	72	24	HHS	2001
Cambodia	98.7	82.0	96.3	1.3	18.0	3.7	DHS	2000
Indonesia	83.2	20.4	72.2	16.8	79.6	27.8	Ag. Cens.	2003
Papua New Guinea	98.2	34.4	89.6	1.7	65.5	10.3	HHS	1996
Yemen, Republic of	53.1	3.0	41.6	46.9	97.0	58.4	HBS	1998

Ag.Cens., Agricultural Census; CWIQ, Core Welfare Indicators Questionnaire; DHS, Demographic and Health Survey; ECAM, Enquête Camerounaise Auprès des Ménages; ECH, Encuesta Continua de Hogares; EHPM, Encuesta de Hogares de Propositos Multiples; ENH, Encuesta Nacional de Hogares; EP, Enquête Prioritaire; EPCES, Enquête Permanente de Conjoncture Économique et Sociale; EPH, Encuesta Permanente de Hogares; HBS; Household Budget Survey; HHS, Household Survey; LSMS, Living Standards Measurement Study; NSS, National Sample Survey; PNAD, Presquisa Nacional por Amostra de Domicilios

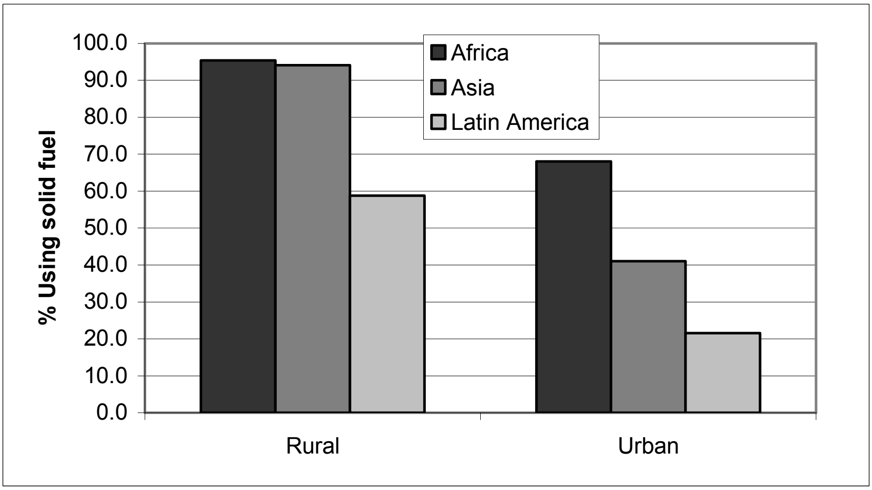
No national survey for China, but other estimates suggest that 50% of urban households have access to LPG.

[a] Most households mix solid and modern fuels.

[b] Surveys involve average of main fuel used.

In Africa, use of biomass is common in both urban and rural areas (Table 1.2; Figure 1.2), and 89% of households in the countries surveyed depend on some type of solid fuel, which includes both biomass and charcoal. In rural areas of Africa, virtually all households use biomass fuels.

Figure 1.2. Percentage use of solid fuel reported as main household cooking energy in national surveys, 1996–2003

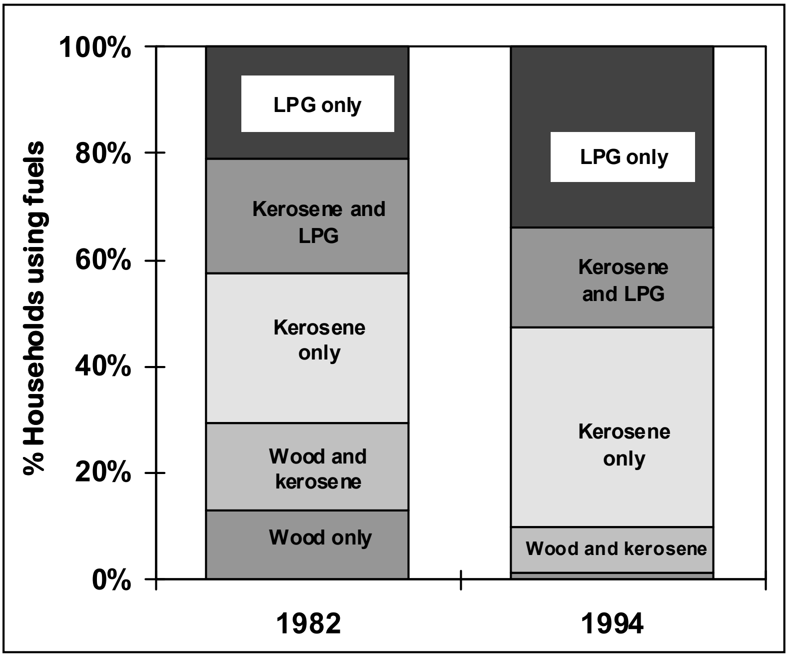


From World Bank (2003)
The figures are based on averages from the countries in Table 1.2.

In Asia, rural areas remain dependent on biomass energy, but many urban areas are increasingly switching to modern fuels (Figure 1.2). Overall, 74% of households in Asia report use of solid fuels, mostly in the form of biomass. However, in countries such as India and China, there are signs of significant change. In a case study in Hyderabad, India (World Bank, 1999; Barnes *et al.*, 2005), most urban people in this large metropolitan area had switched to either kerosene or LPG for cooking in the 1990s (Figure 1.3). Recent national figures in India indicate that only about 20–30% of the urban population uses biomass energy, which is a significant change from 25 years ago. While rural areas are still dominated by biomass or other solid fuels, rising urban incomes and policies to facilitate the heterogeneity of modern fuel use in urban areas, including a significant conversion to kerosene and LPG in Asia, have been the main contributory factors to this trend.

The lack of regular national household energy surveys makes it impossible to quantify with confidence the state of household fuel use, but a variety of evidence can be used to establish estimates with some degree of confidence. For example, in China, the overall picture of household fuel use comes from the National Bureau of Statistics, which prepares national and provincial balances of commercial energy, excluding biofuels (e.g. National Bureau of Statistics, 2006), and the Ministry of Agriculture, which collects and occasionally publishes estimates of biofuel use by province (e.g. EBCREY, 1999). Published data do, however, show that more than 51% of urban households have access

Figure 1.3. Changes in choice of household cooking fuel in Hyderabad from 1982 to 1994



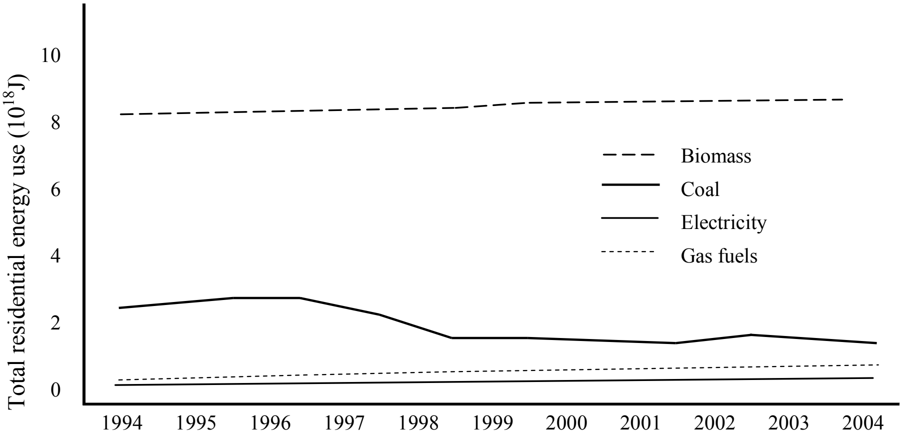
From Barnes *et al*. (2005)
LPG, liquefied petroleum gas

to gas fuels (National Bureau of Statistics, 2005). While access to gas in rural areas is growing, fewer than 10% of rural households use gas fuels as their main cooking fuel (Sinton *et al*., 2004a). All but about 1% of households have at least nominal access to electricity. Despite the rapidly growing availability of electricity and gas, coal and especially biomass remain the overwhelming energy sources for households nationwide (Figure 1.4).

In Latin America, although some extremely poor countries such as Haiti have fuel use patterns that are similar to those seen in Africa, many other countries are switching to modern cooking fuels such as kerosene and LPG (Table 1.2). With the exception of a few countries, less than 10% of the populations in most urban areas in Latin America use biomass energy for cooking (Table 1.2), and the use of modern fuels is also growing in rural areas. For instance, in rural Costa Rica, the use of biomass energy has declined to less than one-quarter of its population, the majority of which has switched to modern fuels.

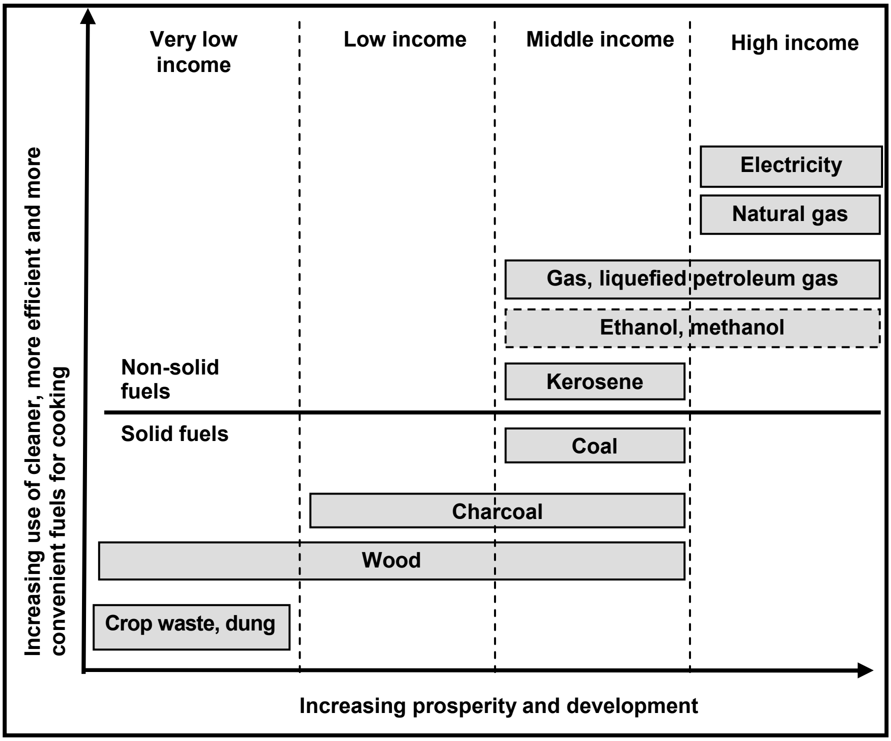
The transition from biomass fuels to modern fuels has been associated with improvement in economic prosperity and development (Figure 1.5). At very low levels of income or development, households depend on biomass fuels such as agricultural waste, dung or firewood. As incomes rise or the country becomes more developed, households

Figure 1.4. Total residential primary energy use in China



From International Energy Agency (2006a,b)

Figure 1.5. Transition from use of biomass fuels to use of modern fuels



From WHO (2006) (Figure 2: The energy ladder: household energy and development inextricably linked)

Note: Ethanol and methanol are rarely, if ever, used.

Dash: estimate

begin to convert to non-solid fuels such as kerosene, LPG or electricity. At middle income levels, households typically use both solid and non-solid fuels.

All over the developing world, significant variations in the use of biomass energy and coal are observed. Both rural and urban populations are switching to modern fuels. However, it is known that very poor countries generally can not afford to use modern fuels, and the richest of countries have already adopted them due to their convenience and cleanliness (see Section 1.4 on intervention and policies).

1.1.4 *Determinants of choice of fuel and energy use*

Most studies have found that three factors determine the choice of fuel (Leach, 1987; Leach & Mearns, 1988; Boberg, 1993; Barnes *et al.*, 2005). The first is access to both modern fuels and to local biomass; the second involves affordability, as determined by household income, since modern fuels must be purchased on the market; the third is the policy options available, such as prices, subsidies and taxes, to reduce dependence on biomass.

(a) Availability and access to biomass and modern energy

The evolution of energy markets in developing countries is irregular. For modern fuels, the institutions that serve both urban and rural markets can be diverse: in some countries, government-run agencies control the flow of kerosene and LPG; in others, there is one dominant supplier that has a virtual monopoly; and in some others, a significant degree of competition exists among a limited number of private companies. In contrast, the supply of biomass is generally characterized by self production or collection of the fuel, local sales, or a market chain that spreads out from urban to rural areas. There is growing evidence that, if households have access to a variety of fuels, a greater acceptance of modern fuels occurs not only in urban (Barnes *et al.*, 2005) but also often in some rural areas.

The type of biomass used in an area largely depends on what is available in the local environment. In Africa, wood is more readily available than in most other parts of the developing world. Most people rely on firewood in rural areas and both firewood and charcoal in urban areas to cook their meals. The use of wood, branches and, increasingly, brush is widespread in Asia and Africa. Dung cakes or balls are used more commonly in Asia and Latin America.

As wood becomes scarce due to deforestation, the use of agricultural residues as a source of energy increases. Crop residues are a very poor source of energy for cooking. In countries in Africa, charcoal is widely available and is thus used to almost the same extent as wood fuels. In China, coal is commonly used to cook and heat. In Bangladesh, a very densely populated country, the amount of local wood available to people is decreasing. A recent survey in Bangladesh (World Bank, 2006) indicated that people who live in areas where access to firewood from the local environment is minimal are turning towards tree leaves, crop residue and dung (Table 1.3). In this situation, people are actually moving down the energy ladder to lower and more polluting fuels. In Bangladesh, very little LPG is available in rural areas. In urban areas, the development of modern cities has resulted in a gradual decline in the use of biomass energy.

Table 1.3. Consumption of energy in domestic activities: all divisions (per household/year: average over all households) in Bangladesh (2005)

Type of energy	All use	Heating		
		Cooking	Parboiling rice	Other
Biomass				
Firewood (kg)	1186	1065	29	93
Tree leaves (kg)	502	471	30	0.9
Crop residue (kg)	708	539	164	2.7
Dung cake/stick (kg)	524	504	16	4.2
Saw dust (kg)	8	8	0.02	0.02
Non-biomass				
Candle (piece)	16	–	–	–
Kerosene (litre)	29	1.8	–	0.07
Natural gas (Tk.)	10	10	–	–
LPG/LNG (litre)	0.05	0.05	–	–
Grid electricity (kWh)	144	0.25	–	4.00
Solar PV (kWh)	0.53	–	–	–
Storage cell (kWh)	0.55	–	–	–
Dry cell battery (piece)	15	–	–	–

From Asaduzzaman & Latif (2005)

As seen in Table 1.4, when the population of a city reaches about 1 million, the use of biomass energy declines sharply, since access to local biomass energy becomes difficult. However, energy policies also play a role in the choice of household fuel. Thus, access to both biomass and modern fuels is an extremely important element in the choice of household fuel.

Table 1.4. Size and energy use in 45 cities in Bangladesh, 1980–88

City type	Population (in thousands)	Monthly income (US $ per capita)	Fuel (%)				
			Firewood	Charcoal	Kerosene	LPG	Electricity
Town	33	38	52	40	33	46	64
Small city	102	41	25	36	37	60	78
Middle city	526	35	47	53	64	23	69
Large city	3718	55	4	28	61	37	95

From World Bank (1988, 1989, 1990a,b,c,d, 1991a,b, 1992, 1993, 1996a, 1999) (hereinafter ESMAP Household Energy Surveys)

LPG, liquefied petroleum gas

(b) *Income and affordability*

Poverty is inextricably linked to the use of biomass. Most homes in developing countries use biomass energy, but there is a growing transition to modern fuels as well as a trend in the opposite direction. Modern fuels cost money–when households can afford to move up the energy ladder and access to modern fuels is not an issue, the transition is almost inevitable.

Affordability is only an issue if there is adequate access to modern fuels, which is often dictated by whether a household lives in an urban or a rural area. In many developing countries, an interesting pattern can be seen between income and fuel use. In the urban areas of India, Nepal, Guatemala and Nicaragua, for instance, the type of fuels used is dependent upon household income: solid fuels are more common among the poorer households and modern fuels are used by the rich. In some large urban areas, even the poor use kerosene and, in some instances, LPG for cooking. In contrast, in the rural areas of these countries, income has less influence on the type of fuel used. Across households of all income classes, solid fuels are common (World Bank, 2003).

In rural areas, affordability largely contributes to the widespread use of biomass energy. Households in rural areas are generally poor and biomass is often available to them from the local environment. The price of using biomass energy is simply the labour required in collecting it (World Bank, 1996a,b; WHO, 2006).

The amount of money spent by the poor on the small quantities of energy that they use is a very important portion of their overall household expenditure. The poor spend less on energy than the more wealthy households, but the percentage of income that they spend on energy is typically much greater. The urban poor spend between 10 and 20% of their income on energy, whereas the wealthy spend less than 5%.

In addition, the cost of energy services for the poor is also higher than that for the rich because cooking with fuelwood and lighting with kerosene are inefficient compared with cooking and lighting with modern fuels. Moreover, the poor often buy fuelwood and charcoal in small amounts, and the higher transaction costs of buying in small quantities inflate the price. Once the comparative efficiencies and transaction costs have been taken into consideration, the delivered energy for cooking often is more expensive for poorer people than for wealthy households.

Poorer people generally use biomass energy except under unusual circumstances. One study based on evidence from 45 cities has classified general points at which people switch from biomass to modern fuels (Barnes *et al*., 2005). Based on income figures given in 1980 US dollars, the study indicated that people start switching from wood at surprisingly low incomes–between US $12 and US $30 per person per month. However, where wood is inexpensive and readily available, people may continue its use at incomes of up to US $100 per person per month. The use of modern fuels, including electricity and LPG, generally intensifies at incomes of about US $40–50 per person per month. This suggests that definitive income ‘cut-offs’ for fuel substitution can not be identified precisely, only very broadly. The reason for this is the variation in access, pricing and government policies. In addition, the study found that modern fuel consumption was higher than that anticipated among poorer households. This can reflect both the attractiveness of modern fuels and particular subsidy policies for some fuels; for example, subsidies for kerosene in Indonesia, coal in China and LPG in some countries.

1.1.5 *Conclusion*

The negative impact of biomass energy on the daily lives of populations (especially women and children) in the poorest parts of the developing world cannot be underestimated. Furthermore, evidence would strongly suggest that the persistent and widespread use of biomass energy largely depends on the factors of access, affordability and pricing policies.

1.2 Constituents of emissions

Wood consists primarily of two polymers: cellulose (50–70% by weight) and lignin (approximately 30% by weight) (Simoneit *et al.*, 1999). Other biomass fuels (e.g. grasses, wheat stubble) also contain these polymers, although their relative proportions differ. In addition, small amounts of low-molecular-weight organic compounds (e.g. resins, waxes, sugars) and inorganic salts are present in wood. During combustion, pyrolysis occurs and the polymers break apart to produce a variety of smaller molecules. Even when they are intrinsically free of contaminants, biomass fuels and coals are difficult to burn in small simple combustion devices such as household cooking and heating stoves without substantial emissions of pollutants, principally due to the difficulty of completely pre-mixing the fuel and air during burning, which is easily done with liquid and gaseous fuels. Consequently, a substantial fraction of the fuel carbon is converted to products of incomplete combustion, i.e. compounds other than the ultimate product of complete combustion, carbon dioxide. For example, typical household coal and biomass stoves in China and India divert between more than 10% and up to ~30% of their fuel carbon into products of incomplete combustion (Smith *et al.*, 2000; Zhang *et al.*, 2000). Emissions of products of incomplete combustion from coal and biomass overlap largely depending on fuel species and stove types.

An individual product of incomplete combustion can be present in the gas phase, particle phase or both phases, depending on its volatility. Hence, products of incomplete combustion released from the combustion of biomass are a complex mixture of particulate and gaseous chemical species, including carbon monoxide, nitrogen dioxide and particulate matter (PM). Products of incomplete combustion also include a large number of hydrocarbons that are precursor components of photochemical smog and comprise ozone, aldehydes and particles (Tsai *et al.*, 2003). Compared with biomass, many coals contain more intrinsic contaminants from their mineral deposits, such as sulfur, arsenic, silica, fluorine, lead and/or mercury. During combustion, these contaminants are not destroyed but are released into the air in their original or oxidized form. Therefore, coal combustion tends to emit other pollutants in addition to products of incomplete combustion. In households that use sulfur-rich coals, for example, sulfur dioxide is present at elevated levels. Since the temperature of coal combustion is normally substantially higher than that of biomass combustion, higher emissions of oxides of nitrogen were measured for household coal combustion than for biomass combustion (Zhang *et al.*, 2000).

Depending on the measurement and analytical methods used, the chemical constituents of biomass and coal smoke have been reported in different studies in the form of individual chemical compounds (e.g. carbon monoxide, benzene, formaldehyde), groups of compounds (e.g. total non-methane hydrocarbon, total organic carbon), elements (e.g. carbon, arsenic) or ions (e.g. fluoride, sulfate). The smoke constituents identified to date are summarized in Tables 1.5–1.7, by class of compound, element and ion, respectively. It should be noted that many of the wood smoke species reported in Table 1.5 were isolated from measurements of US appliances (e.g. woodstoves, fireplaces) and open-field combustion (e.g. wild fire, prescribed forest fire), because few studies have been conducted to characterize detailed chemical speciation for biomass stoves in developing countries. Compounds that are present in emissions from the combustion of wood or coal and have been evaluated by the IARC are listed in Table 1.8. One study has reported emission factors of some 60 hydrocarbons and ~17 aldehydes and ketones from ~28 commonly used fuel/stove combinations in China and emission factors of hydrocarbons from 28 fuel/stove combinations commonly used in India in the early 1990s (Smith *et al.*, 2000; Zhang *et al.*, 2000). In contrast, several hundred individual compounds have been detected in smoke samples of residential wood combustion, wildfire and prescribed burns (Rogge *et al.*, 1998; McDonald *et al.*, 2000; Oros & Simoneit, 2001; Schauer *et al.*, 2001; Fine *et al.*, 2002). Although less well characterized, many of the same chemicals were reported in smoke emissions from other types of biomass, including grasses, rice straw, sugar cane and ferns (Simoneit *et al.*, 1993, 1999; Rinehart *et al.*, 2002). Selected chemicals that are associated with carcinogenicity are discussed below.

Table 1.5. Constituents of biomass smoke and coal smoke, by chemical class

Compound	Wood smoke		Coal smoke	
	Species	References	Species	References
Inorganic compounds	Carbon monoxide	McDonald *et al.* (2006)	Carbon monoxide	
	Sulfur dioxide		Sulfur dioxide	
	Nitric oxide		Nitric oxide	
	Ammonia			

Table 1.5. (contd)

Compound	Wood smoke		Coal smoke	
	Species	References	Species	References
Hydrocarbons				
Alkanes	C_1–C_7	Rogge *et al*. (1998); McDonald *et al*. (2000); Schauer *et al*. (2001); Fine *et al*. (2002); McDonald *et al*. (2006)	C_2–C_{10}	Yan *et al*. (2002); Tsai *et al*. (2003)
Alkenes	C_2–C_7 (including 1,3-butadiene)	Rogge *et al*. (1998); McDonald *et al*. (2000); Fine *et al*. (2002); McDonald *et al*. (2006)	C_2–C_{10} (including 1,3-butadiene)	Yan *et al*. (2002); Tsai *et al*. (2003)
Aromatics	Benzene Xylene Toluene Styrene	Tsai *et al*. (2003) McDonald *et al*. (2006)	Benzene Xylene Toluene Styrene	Tsai *et al*. (2003)
PAHs and substituted PAHs	Acenaphthene Anthracene Benz[*a*]anthracene Benzo[*b*+*j*+*k*]fluorene Benzo[*ghi*]perylene Benzo[*a*]pyrene Benzo[*e*]pyrene Biphenyl acenaphthylene Chrysene Coronene 1,7-Dimethylphenanthrene Fluoranthene Fluorene Indeno[123-*cd*]pyrene 1-Menaphthalene 2-Menaphthalene 1-Methylphenanthrene Naphthalene Phenanthrene Pyrene Retene	Chuang *et al*. (1992); Rogge *et al*. (1998); McDonald *et al*. (2000); Oros & Simoneit (2001); Schauer *et al*. (2001); Fine *et al*. (2002); McDonald *et al*. (2006)	Acenaphthene Acenaphthylene Acephenanthrylene Anthracene Benz[*a*]anthracene Benzanthrone Benzo[*b*]chrysene Benzo[*a*]coronene Benzo[*b*]fluoranthene Benzo[*k*]fluoranthene Benzo[*b*+*j*+*k*]fluorene Benzo[*a*]fluorine Benzo[*b*]naphtha[2,l-*d*]thiophene Benzo[*pqr*]naphtha[8,1,2-*bcd*]perylene Benzo[*ghi*]perylene Benzo[*a*]pyrene Benzo[*e*]pyrene Chrysene Coronene Cyclopenta[*def*]-chrysene-4-one	Chuang *et al*. (1992); Wornat *et al*. (2001); Ross *et al*. (2002); Yan *et al*. (2002); Chen *et al*. (2004, 2005); Lee *et al*. (2005)

Table 1.5. (contd)

Compound	Wood smoke		Coal smoke	
	Species	References	Species	References
PAHs (contd)			Cyclopent[*hi*]acephenanthrylene Cyclopenta[*cd*]benzo[*ghi*]perylene Cyclopenta[*bc*]coronene Cyclopenta[*cd*]fluoranthrene Cyclopenta[*cd*]pyrene Dibenz[*a,c*]anthracene Dibenz[*a,h*]anthracene Dibenz[*a,j*]anthracene Dibenzo[*b,k*]fluoranthene Dibenzo[*a,e*]pyrene Dibenzo[*e,l*]pyrene Dicyclopenta[*cd,mn*]-pyrene Dicyclopenta[*cd,jk*]-pyrene Fluoranthene, Fluorene Indeno[123-*cd*]pyrene Naphtho[1,2-*b*]-fluoranthene Naphtho[2,1-*a*]pyrene 4-Oxa-benzo-[*cd*]pyrene-3,5-dione Phenanthrene Picene Pyrene Triphenylene Tribenzo[*e,ghi,k*]-perylene	
Total non-methane hydrocarbon		McDonald *et al*. (2000); Schauer *et al*. (2001); McDonald *et al*. (2006)		Tsai *et al*. (2003)
Unresolved complex mixture		Oros & Simoneit (2001); Fine *et al*. (2002)		

Table 1.5. (contd)

Compound	Wood smoke		Coal smoke	
	Species	References	Species	References
Oxygenated organics				
Alkanols	Methanol (+ methyl formate) Ethanol (+ acn + acrolein)	McDonald *et al*. (2000); Oros & Simoneit (2001); Fine *et al*. (2002); McDonald *et al*. (2006)		
Carboxylic acids	Heptanoic acid Octanoic acid Nonanoic acid Decanoic acid Undecanoic acid Dodecanoic acid Tridecanoic acid	Rogge *et al*. (1998); Oros & Simoneit (2001); Schauer *et al*. (2001); Fine *et al*. (2002); McDonald *et al*. (2006)		
Aldehydes and ketones	Formaldehyde Acetaldehyde Proponal Butanal Pentanal Octanal Nonanal (+ undecene) Glyoxal Acetone (+ propanal) 3-Buten-2-one Butanone 3-Methyl-3-buten-2-one	Rogge *et al*. (1998); McDonald *et al*. (2000); Schauer *et al*. (2001); Fine *et al*. (2002); McDonald *et al*. (2006)	Formaldehyde Acetaldehyde Acetone Acrolein Propionaldehyde Crotonaldehyde 2-Butanone Isobutyraldehyde Butyraldehyde Benzaldehyde Isovaleraldehyde Valeraldehyde *ortho*-Tolualdehyde *meta*,*para*-Tolualdehyde Hexaldehyde 2,4-Dimethylbenzaldehyde	Miller *et al*. (1994); Zhang & Smith (1999)
Alkyl esters	Nonyl dodecanoate Decyl dodecanoate Undecyl dodecanoate Dodecadienyl dodecanoate Tridecyl dodecanoate	Oros & Simoneit (2001)		
Methoxylated phenolic compounds		Rogge *et al*. (1998); McDonald *et al*. (2000); Schauer *et al*. (2001); Fine *et al*. (2002); McDonald *et al*. (2006)		

Table 1.5. (contd)

Compound	Wood smoke		Coal smoke	
	Species	References	Species	References
Other organic compounds				
Other substituted aromatic compounds	*n*-9-Octadecenoic acid *n*-9,12-Octadecadienoic acid PCDDs PCDFs PCBs	Rogge *et al*. (1998); McDonald *et al*. (2000); Oros & Simoneit (2001); Schauer *et al*. (2001); Fine *et al*. (2002); Gullett *et al*. (2003); McDonald *et al*. (2006)		
Sugar derivatives	1,4:3,6-Dianhydro-R-D-Glucopyranose Galactosan Mannosan Levoglucosan Monomethylinosito	Oros & Simoneit (2001); Fine *et al*. (2002); McDonald *et al*. (2006)		
Coumarins and flavonoids	Coumarin tetramethoxyiso-flavone	Fine *et al*. (2002)		
Phytosteroids	Stigmasterol â-Sitosterol Stigmastan-3-ol Stigmastan-3-one	Rogge *et al*. (1998); Fine *et al*. (2002)		
Resin acids and terpenoids	Pimaric acid Isopimaric acid Abietic acid Levopimaric acid Neoabietic acid	Rogge *et al*. (1998); McDonald *et al*. (2000); Oros & Simoneit (2001); Fine *et al*. (2002)		
Unresolved compounds		McDonald *et al*. (2000); Schauer *et al*. (2001); Fine *et al*. (2002)		

PAH, polycyclic aromatic hydrocarbon; PCB, polychlorinated biphenyl; PCDD, polychlorinated dibenzo-*para*-dioxin; PCDF, polychlorinated dibenzofuran

Table 1.6. Elemental constituents of wood smoke and coal smoke

	Wood smoke (particle phase)		Coal smoke (particle phase)	
	Element	Reference	Element	Reference
	Carbon, including elemental carbon and organic carbon	McDonald *et al*. (2000); Watson *et al*. (2001); Hays *et al*. (2002)	Carbon, including elemental carbon and organic carbon	Watson *et al*. (2001) ; Ge *et al*. (2004)

Table 1.6. (contd)

	Wood smoke (particle phase)		Coal smoke (particle phase)	
	Element	Reference	Element	Reference
Metals	Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Yt, Zr, Mo, Pd, Ag, In, Sn, Sb, Ba, La, Au, Hg, Tl, Pb	Kleeman *et al.* (1999); Watson *et al.* (2001)	Na, Mg, Al, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Yt, Zr, Mo, Pd, Ag, In, Sn, Sb, Ba, La, Au, Hg, Tl, Pb	Kauppinen & Pakkanen (1990); Watson *et al.* (2001) ; Ross *et al.* (2002); Ge *et al.* (2004)
Non-metals	S, P, Si, Cl, Br	Watson *et al.* (2001); Kleeman *et al.* (1999)	S, P, Si, Cl, Br	Watson *et al.* (2001); Ge *et al.* (2004)

1.2.1 *Particles as a whole versus particle components*

Particles emitted from biomass and coal combustion are fine and ultrafine in size (<1 μm in diameter) (Kleeman *et al.*, 1999; Hays *et al.*, 2002). Fresh coal or biomass smoke contains a large number of ultrafine particles, <1 μm in diameter, which condense rapidly as they cool and age. The smoke may contain some larger particles resulting from suspension of ash and solid fuel debris. Because combustion-generated particles and ash/debris particles have different chemical compositions and because particle size determines how deep the particles can travel within and beyond the respiratory tract, ascertaining size distribution plays an important role in the assessment of health impacts (see Section 4). For this reason, there has been a switch in recent studies to the measurement of inhalable (<10 μm, referred to as PM_{10}) or respirable (<2.5 μm, referred to as $PM_{2.5}$) particles rather than of total suspended particles (TSP) as in earlier studies.

A large number of chemical species are contained in combustion particles and many chemical species are not stable (Rogge *et al.*, 1998). Although it is impractical to cover a large number of individual compounds in a single study, a component of a specific physicochemical property may be targeted. For example, total carbon content of particles is a measure of the carbonaceous aerosol. Total carbon may be further segregated into elemental carbon and organic carbon. Although approximately 5–20% of wood smoke particulate mass consists of elemental carbon, the composition of the organic carbon fraction varies considerably with the specific fuel being burned and with the combustion conditions. Elemental carbon has a characteristic carbon core onto which many metals and organic compounds can be readily absorbed or adsorbed.

Earlier studies also focused on different solvent extracts of particles (soot) emitted from biomass or coal combustion. For example, in Xuan Wei County, China, particles released from smoky coal combustion contained the highest amount of organic compounds extractable with dichloromethane, followed by particles released from wood combustion and then by those released from anthracite (smokeless) coal combustion (Mumford *et al.*, 1987). Some combustion emission particles carry stabilized free radicals. Very limited data have shown that free radicals of the semi-quinone type are present in wood smoke particles as well as diesel smoke and cigarette smoke, but not in coal smoke which may contain or carry free radicals of graphite carbon type (Tian, 2005).

Analytical techniques such as ion chromatography can measure chemicals in the extracts of combustion particles in their dissociated form (ions). Commonly identified ions are shown in Table 1.7. These are the most abundant ions in smoke particles.

Table 1.7. Ionic constituents of wood smoke and coal smoke

Ion	Wood smoke (particle phase)		Coal smoke (particle phase)	
	Species	References	Species	References
Anions	SO_4^{2-}	Watson *et al.* (2001); Hays *et al.* (2002); Kleeman *et al.* (1999)	SO_4^{2-}	Watson *et al.* (2001)
	Cl^-		Cl^-	
	NO_3^-		NO_3^-	
Cations	NH_4^+	Watson *et al.* (2001); Hays *et al.* (2002); Kleeman *et al.* (1999)	NH_4^+	Watson *et al.* (2001)
	K^+		K^+	
	Ca^{2+}	Hays *et al.* (2002)		

Table 1.8. IARC evaluations[a] of compounds present in emissions from the combustion of wood or coal

Agent	*IARC Monographs* evaluation of carcinogenicity			*Monographs* volume, year
	In animals	In humans	IARC Group	
Polynuclear aromatic hydrocarbons				
Benz[*a*]anthracene	Sufficient	Inadequate	2B	*92*, 2010
Benzo[*b*]fluoranthene	Sufficient	Inadequate	2B	*92*, 2010
Benzo[*k*]fluoranthene	Sufficient	Inadequate	2B	*92*, 2010
Benzo[*a*]pyrene	Sufficient	Inadequate	1	*92*, 2010
Dibenz[*a,h*]anthracene	Sufficient	Inadequate	2A	*92*, 2010
Chrysene	Sufficient	Inadequate	2B	*92*, 2010
Cyclopenta[*cd*]pyrene	Sufficient	Inadequate	2A	*92*, 2010
Indeno[1,2,3-*cd*]pyrene	Sufficient	Inadequate	2B	*92*, 2010
Naphthalene	Sufficient	Inadequate	2B	*82*, 2002

Table 1.8. (contd)

Agent	*IARC Monographs* evaluation of carcinogenicity			*Monographs* volume, year
	In animals	In humans	IARC Group	
Volatile organic compounds				
Acetaldehyde	Sufficient	Inadequate	2B	*S7*, 1987; *71*, 1999
Benzene	Sufficient	Sufficient	1	*29*, 1982; *S7*, 1987
1,3-Butadiene	Sufficient	Limited	2A	*S7*, 1987; *71*, 1999
Formaldehyde	Sufficient	Sufficient	1	*88*, 2006
Styrene	Limited	Inadequate	2B	*82*, 2002
Metals and metal compounds				
Arsenic	Sufficient	Sufficient	1	*84*, 2004
Nickel	Sufficient	Sufficient	1	*S7*, 1987; *49*, 1990

[a] Only those agents classified as Group 1, 2A or 2B are listed here.

1.2.2 *Polycyclic aromatic hydrocarbons (PAHs) and substituted PAHs*

Polycyclic aromatic hydrocarbons (PAHs) are formed during incomplete combustion of all carbon-based fuels and organic materials, including biomass and coal. At typical ambient temperature, lower-molecular-weight PAHs (with 2–4 aromatic rings) are present predominantly in the gas phase while higher-molecular-weight PAHs are present predominantly in the particle phase. Because PAHs of higher cancer potency are predominantly present in the particle phase (IARC, 2010), combustion particles have often been subjected to compositional analysis for PAHs and PAH derivatives. A detailed analysis of PAHs in the dichloromethane extracts of soot deposits from coal-burning stoves in several homes of Hunan Province, China, identified 32 individual PAHs ranging in size from three to eight fused aromatic rings. The PAHs found in the soot deposits included 20 benzenoid PAHs, six fluoranthene benzologues, one cyclopenta-fused PAH, one indene benzologue, three oxygenated PAHs and one sulfur-containing aromatic (see Table 1.5) (Wornat *et al.*, 2001). Carcinogenic PAHs, methylated PAHs and nitrogen-containing heterocyclic aromatic compounds were detected in large abundance in the particles emitted from smoky coal combustion, as typically found in numerous households in Xuan Wei County,[1] Yunnan Province, China (Mumford *et al.*, 1987; Chuang *et al.*, 1992; Granville *et al.*, 2003; Keohavong *et al.*, 2003). In the aromatic fraction, coal combustion particles appeared to contain higher concentrations and more species of methylated PAHs than wood combustion particles (Chuang *et al.*, 1992).

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[1] Xuan Wei County is a site where decade-long studies have been conducted to examine lung cancer and household coal combustion.

However, profiles of specific PAHs and their abundance vary largely depending on the fuel types and combustion conditions. Between biomass smoke or coal smoke, it is difficult to discern which has the higher PAH content (Tian, 2005).

1.2.3 *Hydrocarbons and partially oxidized organic compounds*

Hydrocarbons identified to date include: in wood smoke—alkanes with 1–7 carbons, and alkenes with 2–7 carbons (including 1,3-butadiene); in coal smoke—alkanes with 1–10 carbons and alkenes with 2–10 carbons (including 1,3-butadiene); in both wood and coal smoke—aromatic compounds (e.g. benzene, xylenes, toluene, styrene) (see Table 1.5). Partially oxidized organic compounds identified in wood and/or coal smoke include alkanols, aldehydes and ketones (carbonyls), carboxylic acids, alkyl esters and methoxylated phenolic compounds. In addition, partially oxidized aromatic compounds and substituted aromatic compounds (e.g. aromatic organic acids, polychlorinated dibenzodioxins, polychlorinated dibenzofurans, polychlorinated biphenyls), sugar derivatives, coumarins and flavonoids, resin acids and terpenoids have been identified in wood smoke (see Table 1.5). Both biomass smoke and coal smoke contain gas-phase carcinogens (e.g. benzene, 1,3-butadiene, formaldehyde) in addition to particle-phase PAHs that have carcinogenic potential. A detailed analysis of organic wood smoke aerosol found nearly 200 distinct organic compounds, many of which are derivatives of wood polymers and resins (see Table 1.5; Rogge *et al.*, 1998).

1.2.4 *Metals and other toxic substances*

Some carcinogenic substances in coal were found to be released into the air during the combustion of lignites used in Shenyang City of northern China and smoky coals used in Xuan Wei County, China. It was reported that lignites from a local Shenyang coal field had very high concentrations of nickel (75 ppm) and chromium (79 ppm) (Ren *et al.*, 1999, 2004) when compared with the levels reported elsewhere in the world (0.5–50 ppm for nickel and 0.5–60 ppm for chromium) (Swaine, 1990). Microfibrous quartz has been found in some smoky coals from Xuan Wei County and the resulting coal smoke but not in wood smoke (Tian, 2005). Particles emitted from burning coals contaminated with toxic elements (e.g. fluorine, arsenic, mercury) in Guizhou Province of China and other areas have been reported to contain high levels of the corresponding elements (Gu *et al.*, 1990; Yan, 1990; Shraim *et al.*, 2003). As shown in Table 1.6, metal and non-metal elements have also been found in wood smoke particles, which reflects the intake of these elements from the soil by trees.

1.2.5 *Emission factors of some carcinogens*

The emission factor of a particular chemical species can be measured as the mass of the species emitted per unit mass of fuel combusted or the mass of the species emitted per unit energy produced or delivered through combustion. A very small number of studies have been conducted to date to quantify emission factors of common pollutants for household stoves used in developing countries.

The available data for selected human carcinogens or probable carcinogens (benzene, 1,3-butadiene, formaldehyde and benzo[*a*]pyrene) are summarized in Table 1.9. The sum of PAHs, when ≥14 individual PAHs were measured, is also shown in Table 1.9. The cited studies measured PAHs most commonly reported in the literature: acenaphthene, acenaphthylene, anthracene, benz[*a*]anthracene, benzo[*b*]fluoranthene, benzo[*a*]-pyrene, benzo[*ghi*]perylene, benzo[*k*]fluoranthene, chrysene, dibenz[*ah*]anthracene, fluoranthene, fluorene, indeno[1,2,3-*cd*]pyrene, naphthalene, phenanthrene and pyrene.

Table 1.9. Emission factors of carcinogenic compounds in the smoke of solid fuel combustion in household stoves (and fireplaces)

Compound	Fuel type	Location (fuel source)	Emission factor[a] (mg/kg fuel)	Emission factor[a] (mg/MJ)	Reference
Benzene					
	Wood (1 type)	China	264–629	159–161[b]	Tsai *et al.* (2003)
	Wood (hardwood)	USA	1190		McDonald *et al.* (2000)
	Fireplace wood (2 types)	USA	225–312		McDonald *et al.* (2000)
	Coal (4 types)	China	2.71–1050	0.9–390[b]	Tsai *et al.* (2003)
1,3-Butadiene					
	Wood (1 type)	China	0.8–1.0	0.2–0.6[b]	Tsai *et al.* (2003)
	Wood (hardwood)	USA	197		McDonald *et al.* (2000)
	Fireplace wood (2 types)	USA	63–95		McDonald *et al.* (2000)
	Coal (4 types)	China	ND–21.3	ND–7.9[b]	Tsai *et al.* (2003)
Styrene					
	Wood (1 type)	China	ND	ND	Tsai *et al.* (2003)
	Wood (hardwood)	USA	117		McDonald *et al.* (2000)
	Fireplace wood (2 types)	USA	35–40		McDonald *et al.* (2000)
	Coal (4 types)	China	ND	ND	Tsai *et al.* (2003)

Table 1.9. (contd)

Compound	Fuel type	Location (fuel source)	Emission factor^a (mg/kg fuel)	Emission factor^a (mg/MJ)	Reference
Formaldehyde					
	Wood (2 types)	China	42–261	18–100^b	Zhang & Smith (1999)
	Wood (hardwood)	USA	246		McDonald *et al.* (2000)
	Fireplace wood (2 types)	USA	113 –178		McDonald *et al.* (2000)
	Coal (3 types)	China	2–51	0.9–12^b	Zhang & Smith (1999)
Acetaldehyde					
	Wood (2 types)	China	41–371	17–145^b	Zhang & Smith (1999)
	Wood (hardwood)	USA	361		McDonald *et al.* (2000)
	Fireplace wood (2 types)	USA	301–450		McDonald *et al.* (2000)
	Coal (3 types)	China	0.8–81	0.3–20^b	Zhang & Smith (1999)
Naphthalene					
	Wood (*Petocarpus indicus*)	Thailand	3.96		Kim Oanh *et al.* (2002)
	Wood (hardwood)	USA	28		McDonald *et al.* (2000)
	Fireplace wood (2 types)	USA	21–55		McDonald *et al.* (2000)
	Wood (eucalyptus chip)	Thailand	39.1		Kim Oanh *et al.* (1999)
	Charcoal	Thailand	7.48		Kim Oanh *et al.* (1999)
	Coal briquettes	Viet Nam	44.5		Kim Oanh *et al.* (1999)
Benzo[*a*]pyrene					
	Wood (*Petocarpus indicus*)	Thailand	0.41		Kim *et al.* (2002)
	Wood (eucalyptus chip)	Thailand	0.69		Kim Oanh *et al.* (1999)

Table 1.9. (contd)

Compound	Fuel type	Location (fuel source)	Emission factor[a] (mg/kg fuel)	Emission factor[a] (mg/MJ)	Reference
Benzo[*a*]pyrene (contd)					
	Wood (hardwood)	USA	0.20		McDonald *et al.* (2000)
	Wood (oak)	USA	0.56		Gullett *et al.* (2003)
	Fireplace wood (2 types)	USA	0.15–0.34		McDonald *et al.* (2000)
	Fireplace wood (3 types)	USA	0.31–0.58		Gullett *et al.* (2003)
	Charcoal (two types)	Kenya	0.01–0.12		Gachanja & Worsforld (1993)
	Charcoal	Thailand	0.17		Kim Oanh *et al.* (1999)
	Sawdust briquettes	Thailand	0.53		Kim *et al.* (2002)
	Coal briquettes	Viet Nam	0.30		Kim Oanh *et al.* (1999)
Benz[*a*]anthracene					
	Wood (hardwood)	USA	0.56		McDonald *et al.* (2000)
	Wood (*Petocarpus indicus*)	Thailand	0.62		Kim *et al.* (2002)
	Wood (eucalyptus chip)	Thailand	0.82		Kim Oanh *et al.* (1999)
	Wood (oak)	USA	0.73		Gullett *et al.* (2003)
	Fireplace wood (3 types)	USA	0.34–0.79		Gullett *et al.* (2003)
	Fireplace wood (2 types)	USA	0.31–0.45		McDonald *et al.* (2000)
	Charcoal	Thailand	0.06		Kim Oanh *et al.* (1999)
	Sawdust briquettes	Thailand	1.04		Kim *et al.* (2002)
	Coal briquettes	Viet Nam	0.11		Kim Oanh *et al.* (1999)

Table 1.9. (contd)

Compound	Fuel type	Location (fuel source)	Emission factor[a] (mg/kg fuel)	Emission factor[a] (mg/MJ)	Reference
Dibenz[*a*,*h*]anthracene					
	Wood (oak)	USA	0.04		Gullett *et al.* (2003)
	Wood (*Petocarpus indicus*)	Thailand	0.15		Kim *et al.* (2002)
	Wood (eucalyptus chip)	Thailand	0.6		Kim Oanh *et al.* (1999)
	Fireplace wood (3 types)	USA	0.03–0.08		Gullett *et al.* (2003)
	Charcoal	Thailand	ND		Kim Oanh *et al.* (1999)
	Sawdust briquettes	Thailand	0.24		Kim *et al.* (2002)
	Coal briquettes	Viet Nam	ND		Kim Oanh *et al.* (1999)
Sum of PAHs (≥14 individual PAHs)					
	Wood (*Petocarpus indicus*)	Thailand	66	0.97[c]	Kim *et al.* (2002)
	Wood (eucalyptus chip)	Thailand	110	5.6[c]	Kim Oanh *et al.* (1999)
	Wood (hardwood)	USA	75		McDonald *et al.* (2000)
	Wood (oak)	USA	147		Gullett *et al.* (2003)
	Fireplace wood (2 types)	USA	80–167		McDonald *et al.* (2000)
	Fireplace wood (3 types)	USA	31–144		Gullett *et al.* (2003)
	Charcoal	Thailand	24.7	0.8[c]	Kim Oanh *et al.* (1999)
	Sawdust briquettes	Thailand	260	6.3[c]	Kim *et al.* (2002)
	Coal briquettes	Viet Nam	102	4.4[b]	Kim Oanh *et al.* (1999)

ND, not detected (below method detection limit); PAH, polycyclic aromatic hydrocarbon

[a] The values are ranges of the means reported in individual studies

[b] Denotes milligrams per megajoule of energy delivered to the pot

[c] Denotes milligrams per megajoule of energy generated through combustion

Fuelwood combustion in two different Chinese cooking stoves generated 264 and 629 mg benzene for every kilogram of wood burned. Burning four types of household coal fuels (honeycomb coal briquette, coal briquette, coal powder and water-washed coal powder) in three different coal stoves generated a very wide range of benzene emissions (2.71–1050 mg/kg fuel) (Tsai *et al*., 2003). When the wood emission factors of benzene have been 'translated' into indoor concentrations for a typical village kitchen, benzene concentrations are expressed in parts per million (Zhang & Smith, 1996). As was the case for benzene, 1,3-butadiene emission factors had a wider range for coal combustion (see Table 1.9). However, wood combustion produced a higher formaldehyde emission factor than that obtained with coal combustion. Using the formaldehyde emission factors, Zhang and Smith (1999) predicted that a wood stove could produce sub-part-per-million and part-per-million peak formaldehyde concentrations in a typical village kitchen, depending on kitchen size and ventilation rate. Emission factors of benzo[*a*]pyrene for wood stoves appeared to be consistent across studies conducted in different countries, depending on fuel species (see Table 1.9). Interestingly, benzo[*a*]pyrene emission factors for fireplaces appeared to be similar to those for wood stoves and to depend on the wood species used. The benzo[*a*]pyrene emission factor for sawdust briquette was within the range of wood stove emission factors. In contrast, benzo[*a*]pyrene emission factors for coal and charcoal appeared to be lower. PAHs combined had the highest emission factor for sawdust briquette and the lowest for charcoal. Wood fuels/stoves (including fireplaces) and coal briquettes had overlaps in emission factor ranges for the PAHs combined. These emission factor patterns (wood versus coal) were, in general, consistent with indoor air concentration patterns measured in households that used coal and wood stoves (see Section 1.3).

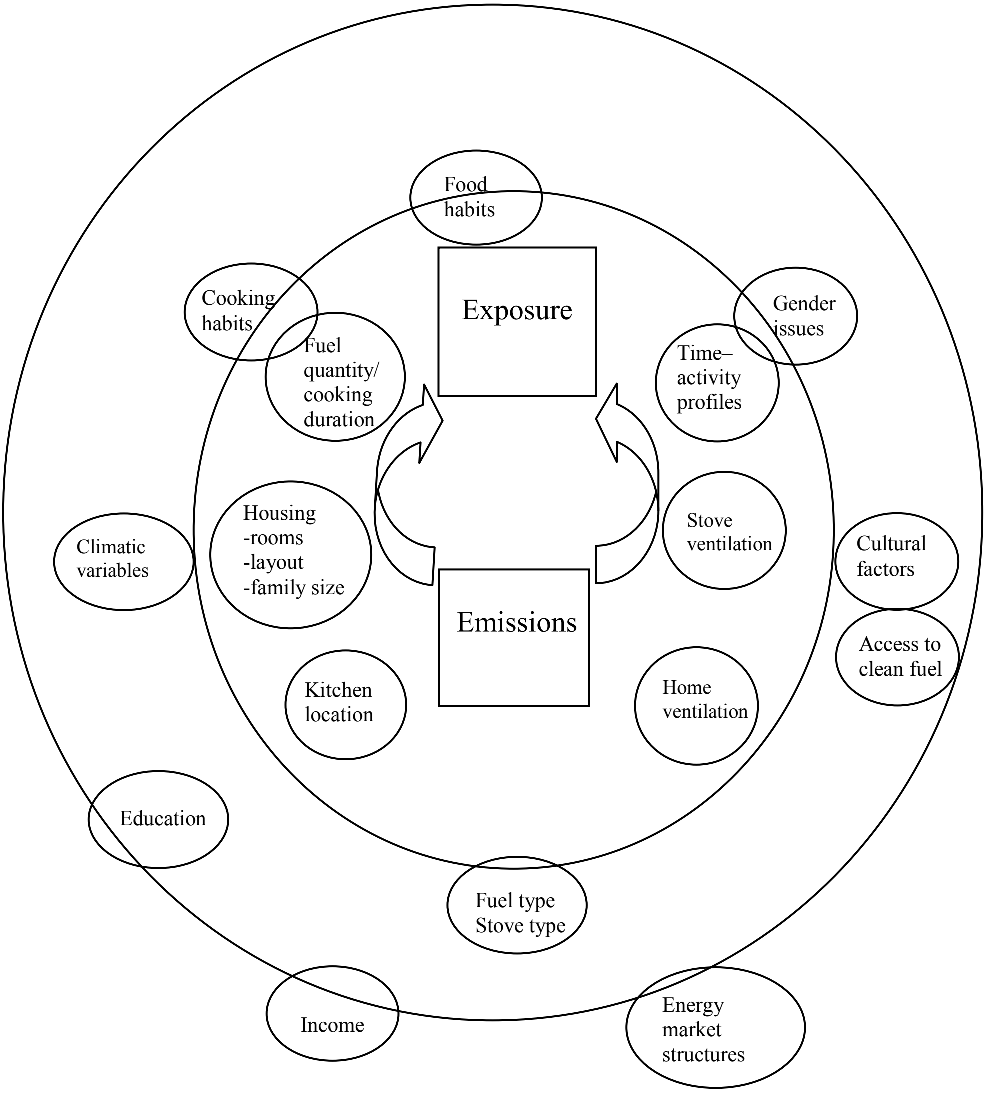
1.3 Use and exposure

1.3.1 *General considerations on exposure to solid fuels*

(a) Determinants of exposure to indoor air pollution

Exposure to indoor air pollution resulting from the combustion of solid fuels is influenced by multiple factors. Individual exposure may be most directly influenced by the interaction of these factors with the source and the surrounding environment. However, many factors can contribute to this interaction indirectly. For example, the type of fuel and room dimensions may directly determine personal exposures but income, climatic conditions, cooking habits and family size may indirectly influence the type of fuel/stove (source) or the dimensions of the living space (surroundings). Determinants of exposure could therefore be described by classifying them broadly into 'proximal' (or 'microenvironmental') determinants that are directly in the exposure pathway and 'distal' (or 'macroenvironmental') determinants that contribute to differences in exposure through their effects on the systems that each of the proximal determinants may represent. Among the studies conducted in developing countries, there is a great deal of similarity in the types of determinant that have been found to affect exposures. Hence, this section gives a general description of these determinants, while their specific contributions to population exposures may be found in individual studies described in Sections 1.3.2–1.3.5. A schematic illustration depicting the causal pathway and its interlinkage with some major classes of determinants is shown in Figure 1.6.

Figure 1.6. A schematic illustration of possible determinants of exposure to indoor air pollution related indoor cooking and heating with solid fuels. The outer circle represents distal determinants while the inner circle represents proximal determinants.



Drawn by the Working Group

(i) *Macroenvironmental (distal) determinants*

Socioeconomic (and demographic) determinants

These determinants operate largely through their influence on choice of fuel (one of the biggest contributors to indoor emissions and exposures, as described in Section 1.1). Income and education can also be expected to affect family size and type of housing that in turn affect fuel quantities or the number of rooms and/or location of the kitchen. Access to cleaner fuels may also be independently influenced by the prevalent national and regional energy market structures, which in turn would be linked to the gross domestic product of individual countries. Countries with a low gross domestic product per capita may experience greater gender inequities in terms of income, education, access to health care, social position and sociocultural preferences, all of which could potentially influence the exposures of vulnerable groups, such as women and children.

Geographic determinants

Although exposures result from indoor sources, external ecological variables can have a significant effect on the intensity and duration of pollution. Extreme temperature differentials between seasons, rainfall, altitude and even meteorological factors such as wind speed, wind direction and relative humidity, for example, could determine whether solid fuels are used for both cooking and heating and also affect aerosol dispersion and/or deposition. Patterns of vegetation (e.g. tropical rain forest versus scrub) could contribute to household decisions to seek alternative energy sources. Conditions of temperature and/or altitude that favour low dispersion (as may be commonly encountered in hilly/cold areas) may also favour higher ambient levels of pollution (resulting from indoor sources) which in turn contribute to increased exposure of the population.

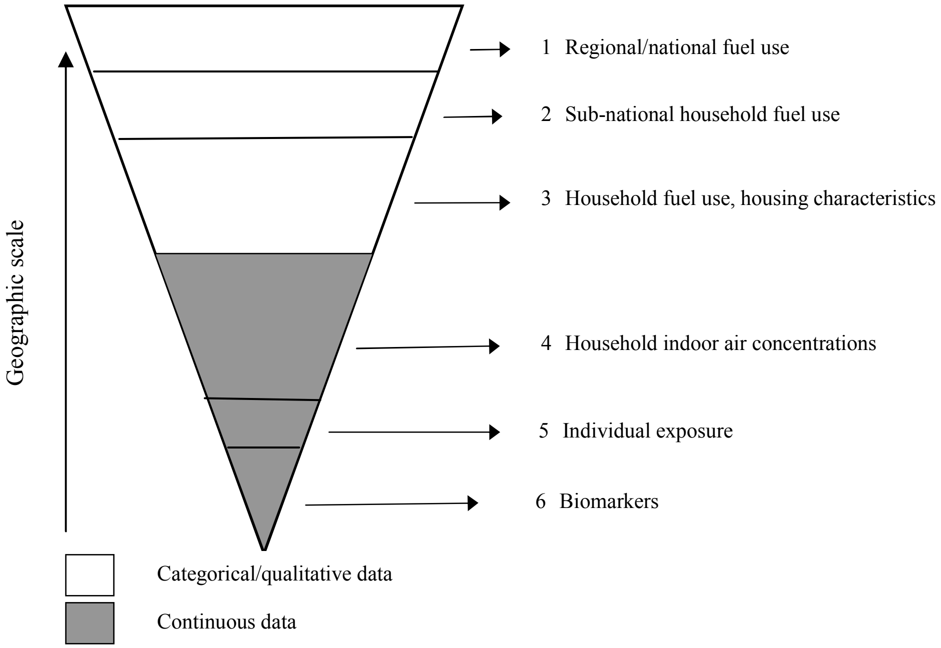
(ii) *Microenvironmental determinants*

While the socioeconomic variables usually influence exposures indirectly through their effect on choice of fuel, several determinants directly influence spatial and temporal patterns of exposure within the household. Use and maintenance of improved stoves, household layout (including the location of kitchen), household ventilation, time–activity profiles of individual household members and behavioural practices (such as location of children while cooking) have been shown to influence pollution levels and individual exposures to them. Cultural habits may influence cooking practices which in turn may affect duration of cooking or the quantity of fuel used. While the available literature does not allow a detailed attribution of exposures to each of these variables, they can be expected to make varying contributions and must be considered when creating local or regional profiles of the exposure situation.

(b) Methods used to assess exposures

Exposures to indoor air pollutants that result from the combustion of solid fuels occur in the homes of millions of people on a daily basis. Multiple determinants affect these exposures directly or indirectly. While it would be impossible to create exposure profiles by routine sampling of thousands of households, systematic assessments that use a combination of qualitative and quantitative methods have been necessary to identify the extent, levels and nature of exposures as well as to understand the relative contributions of specific determinants. An exposure pyramid that illustrates commonly applied approaches used in studies in developing countries is shown in Figure 1.7. As can be seen in the figure in general, as the geographic scale decreases, specificity increases, the availability of pre-existing or routinely collected data decreases and the cost of original data collection increases.

Figure 1.7. A schematic illustration of exposure assessment methods (tiers) used in studies in developing countries (adapted from Mehta & Smith, 2002; Balakrishnan *et al.*, 2004)



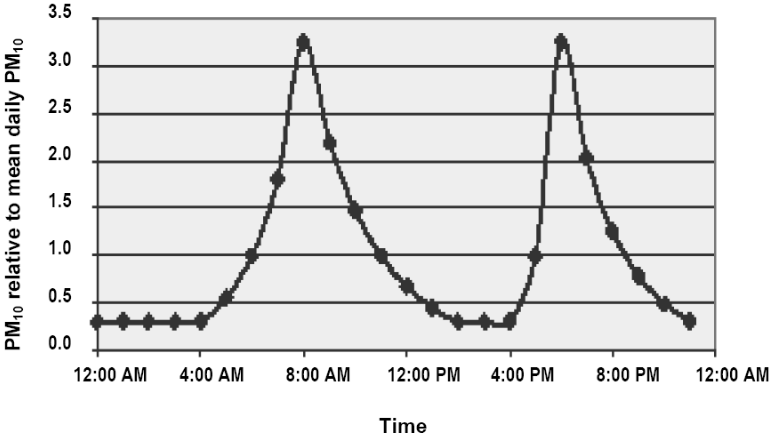
At the top of the pyramid are secondary data sources (tier No. 1). Some qualitative data on exposures, e.g. by primary fuel type, are routinely collected in national surveys such as the census and serve as readily available low-cost exposure indicators, but they often lack precision for estimating exposures at the household level. The influence of multiple household-level variables such as the type of fuel, type and location of kitchen and type of stove on actual household level concentrations/exposures is poorly understood in such assessments. However, this information has been very useful in estimating the proportions of people at risk for these exposures across multiple regions of the world and also in tracking changes in the prevalence of some key determinants such as fuel and stove use in response to policy measures. More accurate (but more expensive) ways to measure exposures are actual household sample surveys of fuel use (tier No. 2). Indeed, this measure has been often used as the indicator of exposure in many epidemiological studies. Even better (but yet more expensive) methods include surveys not only of fuel use, but also of household characteristics such as type of construction material, stove type, number of rooms and windows and room ventilation (tier No. 3). The next stage, which is higher still in cost but more accurate, involves air pollution studies that use stationary air sampling devices set in one or more locations of the household over various lengths of time (tier No. 4). Some studies have been conducted in which people actually wore devices to measure their (personal) exposures to pollution, or in which exposures were reconstructed using concentration data and detailed time–activity–location records of individual household members (tier No. 5). Biological fluid or tissue biomarkers (tier No. 6) have not been applied in field settings, although some laboratory exposure chamber studies have been carried out. Finally, some methods that use a combination of qualitative information on a large number of households together with quantitative and qualitative information on a smaller subset of households have allowed the construction of models that predict levels of household exposure on the basis of qualitative information on selected determinants.

Using methods that collect primary data, a great deal of variation has been observed across studies that estimated either area concentrations or personal exposures (tiers 4 and 5). The choice of sampling locations, the time and duration of sampling, methods/instrumentation used for air sampling and exposure reconstruction coupled with a great deal of interhousehold variability in distribution of determinants such as fuel quantity, room dimensions, ventilation and stove type even within small geographical clusters make it difficult to compare quantitative estimates across studies directly. Of particular importance is the contribution of intense exposures over very short-term periods (i.e cooking periods) within a very small area (usually the kitchen) that often selectively target individual family members (usually women and young children). Figure 1.8 shows a typical distribution of pollutant levels over the course of a day within a single household and illustrates the importance of some of the factors mentioned above for exposures and measurements. The broad range in measurement results described in the following sections thus represents the variation that arises from differences in both exposure and sampling or study methodologies.

1.3.2 *China*

China had a population of nearly 1.3 billion in 2004 (National Bureau of Statistics, 2005). Approximately 757 million lived in rural households, most of whom were dependent on solid fuels for the bulk of their energy needs. Many urban residents also still rely on substantial amounts of coal; relatively few use biomass for occasional tasks. Although household coal is now officially discouraged or banned in all Chinese cities, there is still significant but declining use in many, i.e. 5–10% of households, and a much larger proportion of usage in past decades. Thus, despite rapid urbanization and spread of the use of gas and electricity for cooking and heating, the majority of China's population depends mainly on solid fuels for household energy and is frequently exposed to the products of their combustion. A broad spectrum of information is available on population numbers that use different fuels under various conditions and their resulting pollutant levels (see for instance Impact Carbon (formerly CEIHD) at http://impactcarbon.org/). This information is not complete nor are all sources concordant with each other, but sufficient data exist to enable estimation of ranges of population exposures to a variety of pollutants.

Figure 1.8. Typical variations in PM_{10} level observed during the course of the day relative to daily means



From Mehta & Smith (2002)

(a) *Use and determinants of use of solid fuels*

(i) *Types and amounts of fuel*

The energy yearbooks published by the National Bureau of Statistics (Table 1.10) include some data from the Ministry of Agriculture on household use of biofuels (crop wastes, wood and biogas) by province, but the estimates of fossil fuel consumption in the National Bureau of Statistics' national and provincial balances (which estimate both urban and rural household energy use) differ substantially from those in the relatively rare publications from the Ministry of Agriculture that report the use of fossil fuels in rural households (Table 1.11). National Bureau of Statistics sources report the level of fossil fuel use for rural households to be only about 40% of that cited by the Ministry of Agriculture, possibly due to differences in allocating fuel use to agricultural and household purposes. While the levels of biofuel use are necessarily the same in both sources,

Table 1.10. Household energy use in China, 2004

Category		Original measurements		Conversion into PJ	
	Unit	Urban	Rural	Urban	Rural
Raw coal	Mt	17.33	45.65	409	1077
Washed coal	Mt	3.43	5.55	53	86
Briquettes	Mt	5.39	4.36	96	78
Coke	Mt	0.55	0.51	16	14
Coal gas	Bcm	13.70	0.11	155	1
Gasoline	Mt	2.24	0.63	96	27
Kerosene	Mt	0.02	0.25	1	11
Diesel	Mt	0.84	0.30	36	13
LPG	Mt	11.27	2.24	566	113
Natural gas	Bcm	6.69	0.03	261	1
Delivered heat	PJ	413.95	–	414	–
Electricity	TWh	148.33	98.10	534	353
Crop wastes	Mt	–	339.86	–	4273
Wood	Mt	–	210.92	–	3530
Biogas	Bcm	–	5.59	–	117
Total				2636	9694
Population	Millions	542.83	757.05		
Household size	Persons	2.98	4.08		

From National Bureau of Statistics (2005, 2006)

Mt, million tonnes; Bcm, billion cubic metres; LPG, liquefied petroleum gas; PJ, petajoules; TWh, terawatt–hours

N.B. Biofuel use published in National Bureau of Statistics (2006) is attributed to the Ministry of Agriculture. Data in the same categories as in this table are available from the same sources for nearly all of China's provinces and provincial-level municipalities.

Table 1.11. Rural household energy use in China, 1998

Category	Units		Conversion in PJ
Coal	163.45	Mt	3421
LPG	1.95	Mt	98
Oil products	4.51	Mt	189
Electricity	74.54	TWh	269
Crop wastes	286.24	Mt	3599
Wood	147.13	Mt	2462
Biogas	1.67	Bcm	35
Total			10 074

From EBCREY (1999)

Mt, million tonnes; Bcm, billion cubic metres; LPG, liquefied petroleum gas; PJ, petajoules; TWh, terawatt-hours the difference between estimates of coal use mean that average dependence on biofuels could be approximately between 60% and 80%. Wood accounts for about two-fifths of biofuel use, and crop wastes make up the remainder; biogas use is still very small by comparison. Depending on the data source, coal use in rural households is either of the same order as that of crop wastes, or only a quarter as large.

Nevertheless, available data sources agree on at least one point: overall, rural households in China depend on solid fuels for about 95% of their energy needs. The corresponding proportion for urban households has fallen, and in 2004 was reported to be 22%. This percentage represented nearly 27 million tonnes of coal use. The assessment of the contribution of coal type in different areas of China has been complicated by the fact that the generic terms ‘smoky coal’ and ‘smokeless coal’ are widely applied in both rural and urban China. Generally, it appears that smoky coal is bituminous or sub-bituminous and smokeless coal is anthracite (For distinctions, see the glossary at http://www.eia.doe.gov/kids/energyfacts/sources/non-renewable/coal.html). The more smoky varieties have higher volatile contents, which makes them easier to ignite, but more difficult to burn cleanly in small combustion devices. Furthermore, household coal is frequently mixed with an earth or clay binder and produced as ‘honeycomb’ coal, i.e. in a cylindrical form of standard dimensions with vertical holes that facilitate lighting and combustion. Briquetting is also common. Such mixing has been associated with reduced indoor air pollution emissions, but no systematic testing across the many varieties under household conditions has been done. In addition to the honeycomb form, such mixed forms are variously known as ‘coal cakes’ and ‘coal balls’. The same term probably has different meanings in different places. For example, the term ‘coal cakes’ is used both in rural Xuan Wei and urban Shanghai, although the specific composition of the coal cakes inevitably differs between the two locations and even within each location.

Gas fuels have become more widely available in many areas, and families spend relatively large amounts on their purchase. Government-sponsored projects at the household and village level have brought biogas into many homes, and some biomass gasification projects exist, but these serve a relatively small proportion of the rural population. Only the wealthiest families can afford to use LPG more than occasionally, and household digesters rarely produce enough to satisfy a family’s entire cooking needs; thus, total use of gas fuels remains small.

Ad hoc household energy survey reports provide useful points of comparison in an attempt to establish the broader picture. Tables 1.12–1.15 present some of the information available on energy use at the household level. Survey methods, samples and locations differ among studies; therefore, comparisons of results need to be carried out with care. The information from the National Bureau of Statistics suggests that the average rural household energy use in 2004 was 52 GJ/household–year, or about 13 GJ/person–year. The range of figures in household surveys is spread widely around this average, as do provincial averages derived from statistical publications. Surveys of over 3200 households in six provinces in different regions conducted between 1987 and 1991 found annual household energy use ranging from about 7 to 24 GJ/person–year, compared

Table 1.12. Per-capita energy use in rural households in Liangshui County, Jiangsu Province, and Guichi County, Anhui Province (China), 2003

Location	End use	Energy source (MJ/year)							Total	Share
		Wood	Straw	Biogas	Coal	Kerosene	LPG	Electricity		
Liangshui County, Jiangsu (*n*=356)	Lighting			2		0.3		937	940	16%
	Cooking	1387	735	1258	363		53	109	3904	65%
	Animal feed	260	177	123	11		0.3		571	10%
	Water heating		169	345	46		2		561	9%
	Other		27	3	12				43	1%
	Total	1647	1107	1731	431	0.3	55	1046	6017	
	Share	27%	18%	29%	7%	0.005%	1%	17%		
Guichi County, Anhui (*n*=340)	Lighting							1059	1059	16%
	Cooking	3791		1384			269	13	5457	80%
	Animal feed	45		67					112	2%
	Water heating			197			2		199	3%
	Other			2					2	0.03%
	Total	3836		1650			271	1072	6829	
	Share	56%		24%			4%	16%		

From Wang *et al*. (2006)
LPG, liquefied petroleum gas
Electricity is converted from the value of fuel inputs to power generation.

with the average rural household energy use in 1990 of 11 GJ/person–year (Wang & Feng, 1996; Sinton *et al*., 2004b).

Wang and Feng (1997a,b, 2001) and Wang *et al*. (1999, 2002) have reported a large series of rural energy surveys in eastern China. In a detailed 2003 survey of nearly 700 rural homes in Anhui and Jiangsu in villages where rates of biogas use are very high (24% and 29%, respectively), Wang *et al*. (2006) showed that the level of use of commercial energy remains low (Table 1.12). Including biogas, biofuels accounted for 75–80% of average household energy. Observed energy use *per capita* in these villages which enjoy the mild climate of the central seaboard provinces was about half the national average for rural households. Unlike most surveys, this study also provided a breakdown by end-use which showed that, in these households where no space heating was recorded, cooking tasks far outweighed all others, even when families used large amounts of fuel for the preparation of pig feed. Households without biogas digesters used about 70% more energy—mainly solid fuels—than those with biogas digesters, which provides a basis for estimating the change in exposure resulting from adding gas to the household fuel mix. Notably, LPG use in households with biogas remained significant. An earlier study in Liangshui showed a similar result (Wang & Li, 2005).

In a 2003–04 winter survey of rural areas near Xi'an, in the northern province of Shaanxi, Tonooka *et al*. (2006) found that most of the households used a wide variety of fuels, but most relied mainly on biomass for cooking and heating (Table 1.13). Only 28% of the survey sample, located in a small village, depended mainly on coal. The use of LPG there was also widespread, but was mainly limited to the wealthiest families.

Table 1.13. Stoves and fuels used in rural households near Xi'an, Shaanxi, winter 2003–04

Main stoves and fuels	Cooking		Space heating	
	No. of households	Share	No. of households	Share
Crop residues-*kang*-traditional	110	50%	105	48%
Crop residues-traditional stove	9	4%	5	2%
Crop residues-*kang*-improved	18	8%	17	8%
Crop residues-improved stove	4	2%	0	0%
Twigs-*kang*	2	1%	4	2%
Twigs-traditional stove	5	2%	4	2%
Twigs-*kang*-improved	5	2%	7	3%
Twigs-improved stove	0	0%	0	0%
Coal	35	16%	72	33%
LPG	30	14%	0	0%
Electricity/unknown	0	0%	4	2%
Total	218	100%	218	100%

From Tonooka *et al*. (2006)
LPG, liquefied petroleum gas
A *kang* is a heated brick bed.

A 2002 survey of nearly 35 000 households in Shaanxi, Zhejiang and Hubei—a 10% subsample of which was monitored for indoor air quality (Sinton *et al.*, 2004a,c)—documented the highly diverse fuel and stove use patterns that are typical throughout the country (Tables 1.14 and 1.15). For instance, in the database of households where indoor air quality was measured, 28 different fuel combinations were used in kitchens in winter and 34 different fuel combinations were used in summer (Sinton *et al.* 2004c). In the larger sample of the study, the survey results were generally in line with those arising from national statistics. In some areas, availability of LPG had made improved solid-fuel stoves obsolete, and some households had advanced from traditional solid-fuel stoves directly to LPG. In most cases, however, households used both gas and solid fuels for cooking. Most households in Shaanxi reported that they heated with coal in winter. In Zhejiang and Hubei, where nearly half of the surveyed households did not heat at all in winter, a surprisingly large fraction cooked with charcoal—which is illegal to produce and sell in many areas.

Table 1.14. Main cooking and heating fuels, rural households in Zhejiang, Hubei and Shaanxi, China, 2002

Fuel	Zhejiang		Hubei		Shaanxi	
Main cooking fuel (number of households)						
Wood	807	65.3%	490	43.9%	75	7.0%
Crop residues	300	24.3%	220	19.7%	276	25.9%
Coal	3	0.2%	318	28.5%	686	64.4%
LPG	109	8.8%	69	6.2%	25	2.3%
Electricity	11	0.9%	8	0.7%		
Biogas			6	0.5%	1	0.1%
Charcoal			1	0.1%	1	0.1%
Missing	6	0.5%	3	0.3%	1	0.1%
Total	1236		1115		1065	
Main heating fuel (number of households)						
Wood	231	18.7%	222	19.9%	49	4.6%
Crop residues	5	0.4%	8	0.7%	205	19.2%
Coal	19	1.5%	66	5.9%	750	70.4%
Charcoal	347	28.1%	324	29.1%	1	0.1%
Electricity	59	4.8%	2	0.2%	24	2.3%
LPG and kerosene	5	0.4%	2	0.2%		0.0%
No space heating/missing	570	46.1%	491	44.0%	36	3.4%
Total	1236		1115		1065	

From Sinton *et al.* (2004a)
LPG, liquefied petroleum gas
Wood includes logs, twigs and other woody biomass. Crop residues include other non-woody biomass and dung.

Table 1.15. Types of stove in rural households in Zhejiang, Hubei and Shaanxi, 2002

Stove type	Flue	Zhejiang		Hubei		Shaanxi	
		No. with stove type	Fraction of sample	No. with stove type	Fraction of sample	No. with stove type	Fraction of sample
Traditional biomass	Yes	235	18.9%	60	5.4%	166	15.6%
	No	6	0.5%	50	4.5%	1	0.1%
Improved biomass	Yes	684	55.0%	829	74.3%	212	19.9%
	No	7	0.6%	35	3.1%	6	0.6%
Coal	Yes	3	0.2%	141	12.6%	538	50.6%
	No	145	11.7%	671	60.2%	275	25.8%
LPG	No	723	58.1%	258	23.1%	173	16.3%
Biogas	No	2	0.2%	34	3.0%		
Open Fire	No			121	10.9%		
Other	Yes					90	8.5%
	No	4	0.3%	9	0.8%	85	8.0%

From Sinton *et al*. (2004c)
LPG, liquefied petroleum gas
Many households own more than one type of stove, so the numbers of stove types reported are larger than the household samples (n=3746). Many households also have more than one stove of the same type. In Shaanxi, 'other' stoves probably include some type of coal stove.

(ii) *Stove types, efficiencies and tasks (cooking and heating)*

Programmes to promote improved stoves have long been introduced in China (Smith *et al*., 1993; Sinton *et al*., 2004c). As the survey results in Sinton *et al*. (2004c) described, the complex fuel situation mirrors diverse patterns of stove ownership. Most households surveyed, typically had one or more coal and one or more biomass stoves, and commonly had a gas (LPG or biogas) stove as well. Households with improved biomass stoves commonly had portable coal stoves without flues. Nearly 12% of the households reported having four or more stoves. In the overall survey sample, 95% of the biomass stoves had flues (and 77% were classified as 'improved'); only 38% of the coal stoves were equipped with flues, although most coal stoves are of relatively recent vintage, often burn briquettes and often incorporate convenient and energy-efficient features such as water boilers and small steam/oven chambers.

More than half of the households surveyed used biomass stoves for their main cooking, and about half as many used coal stoves. Many more households had LPG stoves than used them for their main cooking; many use the stoves only occasionally because of the cost of LPG and the ready availability of biofuels in many seasons. Although coal and biomass were commonly used for heating, many households in the sample (especially in Hubei) also used charcoal for heating. It is sometimes difficult to distinguish cooking from heating because cookstoves may be started earlier in the day and left to burn longer in the evening to provide some space heating. Moreover, air pollution and fuel-use surveys in China show a complicated situation in which several fuels and stoves are often in use in different parts of the house in different seasons. In addition to cookstoves and space-heating stoves, for example, the use of *kangs*, which are bed platforms heated from underneath by coal or biomass combustion, is common in different configurations: connected to a cookstove, with a special *kang* combustion chamber fueled from outside, or arranged such that a portable coal stove used during the day for heating and/or cooking is moved under the platform at night. In either case, *kangs* are connected to chimneys, but smoke can nevertheless leak into the bedroom. Most surveyed households—71% in Zhejiang, 80% in Hubei and 81% in Shaanxi—possessed an improved stove of some type. These proportions differed somewhat from the official figures of the Ministry of Agriculture on the wider adoption of improved stoves, but the latter are still indicative of the current predominance of improved stoves. Many small portable coal stoves still do not have chimneys, but are often ignited outside so that their smokiest stage of combustion does not occur indoors. There is also no assurance that the coal types in use today are the same as those used many decades ago in any particular area.

Improvements to biomass stoves have tended to focus on combustion efficiency and the venting of emissions outdoors. However, improved stoves can have higher emissions of pollutants per unit of delivered energy (Zhang *et al.*, 2000). Improved coal stoves in China have been shown to increase exposure to pollutants dramatically since many are unvented (Sinton *et al.*, 2004c).

(iii) *Regional and socioeconomic variation*

Region is highly correlated with socioeconomic status; per-capita income in eastern coastal provinces is typically two to three times higher than that in central and western provinces, for both rural and urban areas (National Bureau of Statistics, 2005). Provincial and national statistical data show that different patterns of fuel use are associated with different socioeconomic and geographical conditions (see Section 1.1). In wealthier provinces, use of electricity and LPG is highest. Where coal resources are richest—generally in the north—coal use is highest. In regions where coal is less readily available and incomes are low, biomass use is highest. In examining Ministry of Agriculture data for rural energy use by province, Wang and Feng (2005) found that, while electricity use was correlated with income, the fraction of total per-capita energy use from biomass was not correlated with income. The use of biofuels was higher in the Anhui households that had incomes more than double those of the Jiangsu households (Wang *et al.*, 2006).

Recent survey results also showed patterns that suggest that solid fuel use does not necessarily decline with rising income, although the use of improved energy forms is positively correlated with income (Sinton *et al*., 2004c). In all three provinces, ownership of improved stoves was associated with lower incomes and, in Hubei and Shaanxi, they were significantly associated with lower levels of education. Fuels followed a similar pattern; the use of commercial fuels (coal, LPG and electricity) was generally associated with higher incomes.

(iv) *Variations between rural and urban locations*

No statistics have been published on biofuel use in urban areas, although a brief assessment of large coastal cities showed that a certain amount of biofuel continues to be used. Relatively large amounts of charcoal are used for cooking and winter heating in some areas according to anecdotal evidence. In terms of the total proportion of urban household energy use, however, the use of charcoal is probably small.

While studies generally reflect the fact that wealthier rural households use more gas and electricity than others and usually only the poorest burn solid fuels in pit stoves, there is a widespread lack of correlation between socioeconomic status and type of solid fuel used and type of stove (traditional or improved) used in rural areas. Tonooka *et al*. (2006) found this in Shaanxi, as did Sinton *et al*. (2004a,c). Wang and Feng (2003) found that, despite higher rates of LPG and electricity use, rural households in wealthy areas still depended on biomass for 50% or more of their energy, and sometimes up to 80%, i.e. to the same extent as households in poorer areas.

(b) Pollutant levels and exposures

Since the 1980s, many studies of indoor air quality in China have been published. The focus in the 1980s and early 1990s was on combustion-related pollutants (Sinton *et al*., 1995). Table 1.16 shows the range of values for particulates (TSP and PM_{10}), benzo[*a*]pyrene, sulfur dioxide, nitrogen oxide and carbon monoxide. For households that use solid fuels, average levels were often in excess of–sometimes several times over–levels set for ambient air quality standards.

In recent years, some attention has returned to combustion products as a result of projects with international participation. Some of these recent studies and a few from the early 1990s are summarized in Saksena *et al*. (2003).

The measured range of levels of particulates is quite wide; means start in the tens of micrograms per cubic metre, but more typically reach into the hundreds of micrograms per cubic metre, or even well into the thousands, as shown in Table 1.17—a sample of the many monitoring studies carried out. Most monitoring has focused on TSP, although PM_{10} is much more common now, and a few studies have examined PM_4 and smaller fractions. Studies of PM_{10} levels in kitchens during meal preparation indicate that cooks are exposed daily to levels of 600 $\mu g/m^3$ or even three times that much. A recent study examined winter levels of PM_4 in households in Guizhou and Shaanxi, in areas where coal is contaminated with fluorine, and found that average levels in kitchen and living areas were from about 200 μg/m^3 to 2000 μg/m^3 (He *et al.*, 2005).

Table 1.16. Indoor air pollution in Chinese residences: ranges of pollutant levels in research articles (1982–94) (arithmetic means)

Pollutant	**Fuel**	**Urban (mg/m^3)**	**Rural (mg/m^3)**	**Standards[a] (Class II, mg/m^3)**	
TSP	Coal	0.21–2.8	0.01–20	Daily average	0.3
	Gas	0.15–0.51	0.19	Max. at any time	1
	Biomass		0.17–2.6		
PM_{10}	Coal	0.16–2.7	0.12–26	Daily average	0.15
	Gas	0.14–0.45	–	Max. at any time	0.5
	Biomass		0.83–22		
CO	Coal	0.58–97	0.70–87	Daily average	4
	Gas	0.22–36	2.4	Max. at any time	10
	Biomass		0.5–16		
SO_2	Coal	0.01–5.8	0.01–23	Annual average	0.06
	Gas	0.01–1.3	0.02–0.07	Daily average	0.15
	Biomass		0.01–9.1	Max. at any time	0.5
NO_x	Coal	0.01–1.8	0.01–1.7	Daily average	0.1
	Gas	0.01–0.88	0.03–0.05	Max. at any time	0.15
	Biomass		0.01–.32		
BaP (ng/m^3)	Coal	0.3–190	5.3–19 000		
	Gas	4.7–93	–		
	Biomass		3.7–3100		

From Sinton *et al.* (1995)

BaP, benzo[*a*]pyrene; CO, carbon monoxide; Max., maximum; NO_x, nitrogen oxide; PM, particulate matter; SO_2, sulfur dioxide; TSP, total suspended particles

[a] Class II air quality standards are intended to protect human health and apply to residential areas.

Particulate levels are typically lower in summer, sometimes by an order of magnitude, but this is not the case universally. While differences in indoor pollutant levels between similar households that use solid fuels and gas fuels are clear, the differences between solid fuels are not always evident. Studies in Inner Mongolia and Gansu have shown that dung fuels lead to both higher and lower levels of PM_{10} than coal in similar households (Jin *et al.,* 2005). Furthermore, as can be seen in Figure 1.9, coal use in rural areas can apparently be cleaner than use of biomass. This alone could account for the large difference in the range of concentrations found between urban and rural households that

Table 1.17. Selected studies with quantitative measurements of particulates in indoor air pollution related to the use of solid fuel in China

Reference	Household location	No. of households	Season	Fuel	Stove type	Particulate type	Mean[a] (μg/m^3)	CV	Range	Sampling location	Sampling duration	Method
Short-term (e.g. cooking)												
Zhao & Long (1991)	Baodong, Sichuan Province	Rural 4		Raw coal	No flue	PM$_{10}$	710		0.31–1.26	Kitchen	Cooking	
	Pengshui, Sichuan Province	3		Briquette			930		0.48–2.39			
	Qinjiang, Sichuan Province	4		Anthracite			970		0.43–2.04			
	Zigui, Sichuan Province	Rural 5		Anthracite			1120		0.11–2.23			
	Wushan, Sichuan Province	5 3		Raw coal Anthracite			1810 1260		0.61–4.55 0.22–3.29			
Gao *et al.* (1993)	Changsha, Hunan Province	Rural 5 4	Summer	Coal Wood		PM$_{10}$	640 1060	550 (SD) 1050 (SD)		Kitchen	Cooking (2–3 day avg)	

Table 1.17 (contd)

Reference	Household location	No. of households		Season	Fuel	Stove type	Particulate type	Mean[a] (µg/m^3)	CV	Range	Sampling location	Sampling duration	Method
Smith *et al.* (1994)	Beijing	Urban	58		Coal	Improved	PM_{10}	1900	0.6			Meal	Cyclone
Longer-term													
Zhang (1988)	Gansu Province	Rural	4		Cow dung		TSP	3020	120	2558–3623		3-day avg	
			4		Coal			3765	399	1876–5117			
Chang & Zhi (1990)	Inner Mongolia	Rural	15	Winter	Dung		TSP	1939				Daily average	
							PM_{10}	1674					
				Summer			TSP	1061					
							PM_{10}	830					
			6	Winter	Coal		TSP	1743					
							PM_{10}	500					
				Summer			TSP	1559					
							PM_{10}	393					
Qin *et al.* (1991)	Chengde, Hebei Province	Urban	15	Winter	Coal	Traditional	TSP	665			Breathing zone	24 h	Cyclone
				Summer			TSP	63					
	Shenyang, Liaoning Province	Urban	15	Winter	Coal	Traditional	TSP	651					
				Summer			TSP	125					
	Shanghai	Urban	15	Winter	Coal	Traditional	TSP	384					
				Summer			TSP	411					
	Wuhan	Urban	15	Winter	Coal	Traditional	TSP	291					
				Summer			TSP	112					

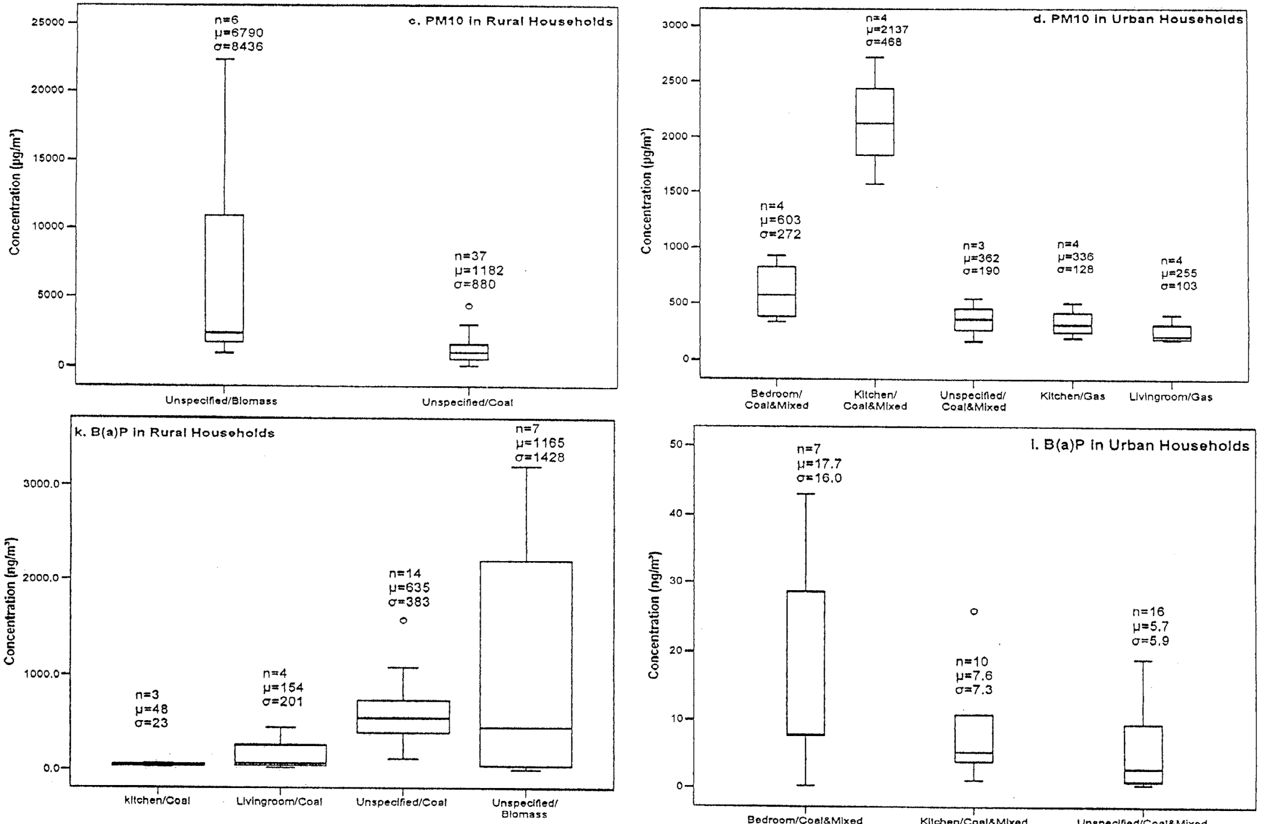
Table 1.17 (contd)

Reference	Household location	No. of households		Season	Fuel	Stove type	Particulate type	Mean[a] (µg/m³)	CV	Range	Sampling location	Sampling duration	Method
Xu & Wang (1993)	Haidian, Beijing	Urban	31	Summer	Coal	Traditional	TSP	41	139		Bedroom	8 h	Gravimetric
	Dongcheng, Beijing	Urban	8	Summer	Coal	Traditional	TSP	90	110		Bedroom	8 h	
	Shijingshan, Beijing	Urban	10	Summer	Coal	Traditional	TSP	152	137		Bedroom	8 h	
Venners *et al.* (2001)	Anqing, Anhui Province	Rural	165	Summer	Wood		PM_{10}	248			Kitchen and bedroom		Gravimetric
Lan *et al.* (2002)	Xuanwei, Yunnan Province	Rural	15		Coal	traditional (*n*=2); improved (*n*=13)	PM_{10}	2080			1.2 m	24 h/day, 5 consecutive days	Gravimetric

[a] Data are arithmetic means.

avg, average; CV, coefficient of variation; PM, particulate matter; SD, standard deviation; TSP, total suspended particulates

Figure 1.9. Concentrations of pollutants measured in households that use solid fuel, China



From Sinton *et al.* (2004b)

The central line of each box plot indicates the sample median. The tops and bottoms of the boxes represent 75th percentiles, and the top and bottom horizontal lines represent the 95th percentiles.

B(a)P, benzo[*a*]pyrene; PM, particulate matter use solid fuels. The former are exposed to much lower levels of PM_{10}, but the levels are still significantly higher in general than recognized ambient and/or indoor standards.

The impact on indoor air quality of improved stoves is similarly dependent on particular circumstances. For instance, improved stoves do not always have lower emissions factors (Zhang & Smith, 1999). Confounding factors such as differences in fuel combinations, shifting patterns of tasks and fuel use over time and use of multiple stoves may all influence exposure levels. The three-province survey (Sinton *et al*., 2004a) found that, taking smoking into account, in summer when stove use was dominantly for cooking, households that used coal experienced higher particulate (PM_4) levels than those that used biomass combinations, and traditional stoves emitted higher particulate levels than improved stoves (Table 1.18). Such differences disappeared during the winter heating season, however, when many households used unvented stoves; tobacco smoke was a confounding factor throughout. Even in summer and in households with no smokers, average PM_4 levels were in the range of 180–450 μg/m^3.

The same study (Sinton *et al*., 2004a) found that, in some cases, kitchens were not the sites with the highest average particulate levels. Those households that used coal or a combination of coal and biomass, unlike those that used biomass or a combination of biomass and gas, had higher particulate levels in living rooms than in kitchens. In living rooms, heating, smoking and perhaps other factors can result in levels over time that are higher than those in kitchens, despite the peaks associated with cooking. Among all the fuel combinations, average winter levels ranged from just under 100 to over 300 μg/m^3.

A recent survey of indoor air in households that used coal and biomass fuels in four provinces (Jin *et al*., 2005) showed that a variety of stove and fuel combinations in different seasons leads to average PM_4 levels in the hundreds of micrograms per cubic metre (Table 1.19). Differences between rooms with and without stoves were small.

A large number of studies that monitored benzo[*a*]pyrene were restricted to households in Xuan Wei County, Yunnan Province, but many others have reported assays performed elsewhere (Table 1.19). Measured indoor levels of benzo[*a*]pyrene were in a range spanning four orders of magnitude, from single digits (1.16 ng/m^3) to over 10 000 ng/m^3 in some of the studies in Xuan Wei County, in which bituminous coal led to much higher indoor levels than anthracite. In studies performed in other parts of the country, household averages rarely exceeded 40 ng/m^3. The relative preponderance in the literature of the Xuan Wei County studies may account in part for the difference observed in a comparison of the results of monitoring studies in urban and rural households that used solid fuels (Figure 1.9).

The combustion of wood fuels (using traditional stoves) emits levels of benzo[*a*]pyrene that fall within the range found in households that use coal (in improved stoves), and, in fact, have an upper range that far exceeds that found in the studies of coal. In the households in Xuan Wei County that used wood fuels (using traditional stoves), levels were often much higher than those in households that used coal (in improved stoves) in other parts of the country, which highlights the role played by stove type.

Table 1.18. Indoor air pollution levels in rural households in Hubei and Shaanxi, summer 2002

Room	Fuel	Smoking		PM$_4$ (μ/m$^{3)}$	HOBO CO (mean ppm)	CO Dosimeter tube (ppm)
Living room	Wood twigs, agricultural residues, coal	Yes	N	15	5	5
			Mean	**316**	**1**	**38**
		No	N	8	2	2
			Mean	**235**	**0**	**23**
	Agricultural residues, coal	Yes	N	130	13	14
			Mean	**341**	**17**	**130**
		No	N	58	4	6
			Mean	**222**	**1**	**20**
	Coal products	Yes	N	79	15	16
			Mean	**301**	**11**	**85**
		No	N	51	8	8
			Mean	**284**	**17**	**73**
	Kruskal Wallis test		Asymp. Sig.	0.36	0.09	0.00

Table 1.18 (contd)

Room	Fuel	Smoking		PM$_4$ (μ/m^{3})	HOBO CO (mean ppm)	CO Dosimeter tube (ppm)
Kitchen	Wood twigs, agricultural residues, coal	Yes	N	15	4	5
			Mean	**478**	**4**	**38**
		No	N	8	1	2
			Mean	**191**	**0**	**23**
	Agricultural residues, coal	Yes	N	37	5	6
			Mean	**418**	**11**	**147**
		No	N	16	1	2
			Mean	**188**	**3**	**25**
	Coal products	Yes	N	29	3	4
			Mean	**263**	**8**	**125**
		No	N	15	2	2
			Mean	**451**	**35**	**125**
	Kruskal Wallis test		Asymp. sig.	0.29	0.06	0.00

From Sinton *et al*. (2004a)

Asymp. sig., asymptote significance; co, carbon monoxide; N, number; PM, particulate matter

N.B. Most households that use agricultural residues and wood also used some coal.

Table 1.19. Concentrations of PM_4 in rural households in four provinces in China, 2003

Province	Primary cooking fuel	Primary heating fuel	Indoor location	Month	No. of observations	Mean (µg/m^3)	95% CI
Gansu	Biomass	Biomass with some coal	Kitchen	March	96	518	364–671
				December	33	661	467–855
			Living/bedroom	March	96	351	205–500
				December	33	457	280–634
Inner Mongolia	Biomass	Coal and biomass	Single room (pt 1)	December	61	718	538–898
			Single room (pt 2)		61	719	480–958
Guizhou	Coal	Coal	Kitchen	March	96	352	224–480
				December	32	301	178–425
			Living/bedroom	March	96	315	186–443
				December	32	202	159–245
Shaanxi	Biomass and coal	Coal	Kitchen	March	100	187	143–230
				December	36	223	164–282
			Living room	March	25	215	136–293
				December	29	329	261–397
			Bedroom	March	98	186	132–241
				December	24	361	266–355

From Jin *et al*. (2005)
CI, confidence interval

Some time–allocation (time–activity) survey data have been published but they do not provide information regarding indoor environments (e.g. Ohtsuka *et al*., 1998; Jiang *et al*., 2006). A few studies of exposures to pollution and health impacts include the gathering of time–allocation information (Table 1.20). Pan *et al*. (2001), for instance, monitored indoor air quality in several locations from rural residents in Anqing, Anhui Province, and found that exposure to PM_{10} was dominated by the time spent indoors where levels were up to twice as high as those outdoors (Table 1.21).

1.3.3 *South Asia*

South Asia has nearly 1.5 billion inhabitants, who account for approximately a quarter of the world's population. Since nearly 70% of the population of this region lives in rural areas (WHO, 2005a) and approximately 74% relies on solid fuels for household energy requirements (Rehfuess *et al*., 2006), the region accounts for a major fraction of global exposure to indoor air pollution from smoke that is attributable to combustion of solid fuels. Recent estimates of disease burdens calculated by WHO indicate that nearly 4% of the disease burden in the region may be attributable to consequent exposures, and women and children under the age of 5 years bear the largest share of this burden (WHO, 2002,

Table 1.20. Selected studies with quantitative measurements of benzo[*a*]pyrene in indoor air pollution related to the use of solid fuel in China

Reference	Household location		No. of house-holds	Season	Fuel	Stove type	Mean[a] (ng/m^3)	CV	Range	Sampling location	Sampling duration	Method
Short-term (e.g. cooking)												
Yunnan Province Health Station (1984)	Xuanwei, Yunnan Province	Rural	6	1977	Bituminous coal	*Kang*	453.2		18.3–5992.4	Living room	Meal preparation	Fluorescence spectrometry
			6		Anthracite	*Kang*	69.1		17.7–191.7	Living room		
Yang *et al.* (1988)	Xuanwei, Yunnan Province	Rural	1		Wood		67.5				2 h	Fluorescence spectrometry
			1		Bituminous coal		399.1					
			1				295.5					
			1		Anthracite		8.5					
			1				25.5					
Longer-term												
Guo & Tang (1985)	Nanning, Guangxi Province	Urban	3	Autumn	Coal briquette		1.2			Kitchen	2-day averages	
			2				4.1					
			3				1.4					
Mumford *et al.* (1987)	Xuanwei, Yunnan Province		8	Autumn	Coal	Improved	13.4		4–21	1.5 m	12 h	GC/MS
		Rural	4	Autumn	Wood		3100	0.323				
			4		Bituminous coal		14 700	0.204				
			1		Anthracite		600					

Table 1.20 (contd)

Reference	Household location		No. of households	Season	Fuel	Stove type	Mean[a] (ng/m³)	CV	Range	Sampling location	Sampling duration	Method
Wang *et al.* (1989)	Harbin, Heilongjiang Province	Urban	13	Winter	Coal		34.0		10.6–59.8	Bedroom	3-day averages	Fluorescence spectrophotometry
			4				43.1		26.7–51.1			
			4				23.4		10.6–39.9			
Du & Ou (1990)	Guangzhou, Guangdong Province	Urban	20	4-season average	Coal		13	0.754				
He *et al.* (1991)	Xuanwei, Yunnan Province	Rural	27		Coal/wood/ smokeless coal different composition %	Traditional	76.1				12 h/day for 3 consecutive days	Fluorescence spectrophotometry
Xian *et al.* (1992)	Xuanwei, Yunnan Province	Rural			Wood		25		6.3–75		24 h TWA	Personal monitoring
					Bituminous coal		110		69–180			
Guo *et al.* (1994)	Taiyuan, Shanxi Province	Urban	8	Winter	Briquette	F	7.9			Apartment bedroom	3-day averages	
			8		Briquette	F	10.9			Apartment kitchen		
			3		Briquette	F	7.3			Single-storey dwelling		
Liu *et al.* (2001)	Zhejiang Province	Urban	8	Summer	Coal	Improved	10		2–17	1.5 m	12 h	HPLC

Table 1.20 (contd)

Reference	Household location		No. of households	Season	Fuel	Stove type	Mean[a] (ng/m^3)	CV	Range	Sampling location	Sampling duration	Method
Lan *et al.* (2002)	Xuanwei, Yunnan Province	Rural	15		Coal	Traditional (2); improved (13)	1660			1.2 m	24 h for 5 consecutive days	HPLC

CV, coefficient of variation; GC/MS, gas chromatography/mass spectrometry; HPLC, high-pressure liquid chromatography; L, living room; TWA, time-weighted average

[a] Data are arithmetic means

Table 1.21. Indoor air pollution in levels, time budgets and exposures in rural residences, Anqing, Anhui, China

Indoor pollutant levels (geometric means±SD)

Location	Sample size	PM_{10} (µg/m^3)	SO_2 (µg/m^3)	CO (mg/m^3)
Kitchen	373	518±27	12.4±36	2.0±9.9
Bedroom	504	340±9	10.9±18	1.6±6.0
Living room	366	287±9	11.0±19	1.6±4.5
Outdoor (among crops)	55	270±10	10.8±18	2.0±4.5

Time allocation (arithmetic means±SD)

Location	Male (n=245)	Female (n=222)
Kitchen	1.36±2.15	3.78±2.48
Bedroom	9.59±4.09	10.56±3.59
Living room	2.44±2.51	2.69±2.16
Outdoor (among crops)	0.84±2.66	0.62±1.49
Other	8.87±6.12	5.07±6.06

Personal average daily exposures

Pollutant	Sex	Sample size	Geometric means±SD
PM_{10} (µg/m^3)	Male	201	556±535
	Female	175	659±646
SO_2 (µg/m^3)	Male	194	23±67
	Female	170	25±70
CO (mg/m^3)	Male	193	2.25±1.6
	Female	169	2.5±2.4

From Pan *et al.* (2001)
CO, carbon monoxide; PM, particulate matter; SD, standard deviation; SO_2, sulfur dioxide

2005b). Nearly all countries in the region are classified as belonging to medium or low human development categories (UNDP, 2001) and the profile of several determinants of indoor air pollution that result from cooking and heating is similar within countries of the region.

Given the heterogeneous, decentralized nature of exposures across multiple geographical zones and the limitations of financial and technical capacity, few large-scale quantitative assessments have been possible in this region. Exposure assessments have involved multiple levels of accuracy and resolution and ‘representative’ exposures are therefore difficult to describe. Nevertheless, an attempt has been made to describe the levels of indoor air pollution in relation to specific determinants that operate at the household (microenvironmental), socioeconomic and geographical (macroenvironmental) levels.

(a) Exposure data

Since they are currently outside the regulatory purview in most countries of the region, methods for the measurement of indoor air pollution have followed considerations of research as opposed to uniform protocols in adherence to national or international standards. Field logistics, contributions from multiple determinants and resource limitations have further contributed to additional challenges in making such measurements. Exposure assessments/estimations have thus been made on different scales with various levels of accuracy and resolution, in large part by individual research groups. As described earlier (Figure 1.9), the methods used in the region have ranged from fuel surveys to quantitative assessments of one or more pollutants under multiple exposure configurations. A few studies have also developed models to estimate exposure potentials. Accordingly, the results of exposure studies in the region are described below, by broadly classifying them as qualitative or quantitative assessments.

(i) *Qualitative studies of exposure*

Methods that rely on categorical qualitative variables collected from large populations can be expected to be less accurate and representative than those based on direct measurements of household or individual levels. However, as described below, every single quantitative measurement in this region unequivocally points to overwhelming pollution loads in homes that use solid fuel, which are often an order of magnitude higher than those in homes that do not use such fuels and several fold higher than commonly available exposure guidelines for specific pollutants. This has allowed ‘reported solid fuel use’ to be used quite reliably as a proxy for exposure in many epidemiological studies. Furthermore, the inclusion of information on the use of fuel in routinely administered population-based surveys, including national census surveys in many countries of this region, has allowed the generation of regional, national and sub-national estimates for percentages of total population at risk of such exposures to indoor air pollution. Exposure estimates recently generated by WHO (2002) for the purposes of assessing attributable (region-specific/global) disease burdens are an example of such an exercise. Results from selected recent studies that provided estimates of country levels are summarized in Table 1.22.

Information on several determinants (described in the previous section) other than the use of fuel has been collected in some national and many regional surveys. Many of these determinants are not independently associated with exposures to indoor air pollution and their contributions may be significant, but remain secondary to the type of fuel used. Many of these have, however, been found to be useful for extrapolation in models in which either data on fuel use have not been available (e.g. using data on income, education, energy market structures) or for further stratification of exposures on the basis

Table 1.22. Studies that reported percentages of solid fuel use in countries of South Asia as an indicator of the fraction of the population exposed

References	India	Pakistan	Thailand	Nepal	Sri Lanka	Bangladesh	Malaysia	Viet Nam	Indonesia	Korea
Mehta & Smith (2002); Desai *et al*. (2004); Smith *et al*. (2004)[a]	81	76	72	97	**89**	96	29	98	63	**68**
Rehfuess *et al*. (2006)[b]	74	72	72	80	67	88	<5	70	72	
Smith (2000)[c]	81	460 million people (~52% of the 1991 population) were estimated to be at risk of full exposure and nearly 252 million (~30% of the 1991 population) at risk of partial exposure in India								
Wickramsinghe (2005)[d]					83	15 million people (~83% of total and nearly 100% of the rural population in 1991) relied on solid fuels in Sri Lanka.				
Choudhari & Pfaff (2003); SCEA report (2006)[e]		67	86% of rural and 32% of urban households used solid fuels with a weighted average of 67% in Pakistan. The latter reference cites an 80% overall prevalence of solid fuel use based on routine data from a subset of 4800 households.							

[a] Global household fuel use database compiled using data from the national census, US Bureau of Census and UN Statistics Division wherever available and modelled (shown in bold) using demographic variables for other countries (as described in Mehta & Smith, 2002, Smith *et al*., 2004) using 1991 as the base year for census data.

[b] Global household fuel use database compiled using data from Demographic Health Survey (DHS, 2004), The World Health Survey (WHS, 2005) and The World Bank Living Standards Measurements Study (LSMS, World Bank 2006), wherever available and modelled using demographic variables, for other countries (as described in Mehta & Smith, 2002; Smith *et al*., 2004).

[c] Indian National Census data (1991) and data from The National Family Health Survey (1992), a population weighted national sample survey, was used to the extract information on household fuel use and related demographic variables.

[d] Data cited in a report compiled from the Food and Agricultural Organization (FAO) initiatives on Community Forestry and Regional Wood Energy Development Programme; no additional details are available.

[e] Data from Pakistan National Census Survey (1998) and The Pakistan Integrated Household Survey (PIHS, 1991) a national survey implemented jointly by the Federal Bureau of Statistics, Government of Pakistan and World Bank (as a part of the World Bank LSMS survey) was used to extract data on fuel use and related demographic variables. Census estimates were considerably lower than PIHS estimates.

of other quantitative studies (e.g. using data on stove type, ventilation, kitchen location, age, gender). Results from a selection of such studies are provided in Table 1.23.

Table 1.23. Studies that reported household survey/modelled data for potential exposures related to the use of solid fuel in South Asia

Country	Description of study results	Reference
Bangladesh	Quantitative measurement (of PM_{10}) results and determinant information from a stratified sample of 236 homes were extrapolated using regression models to predict air pollution levels in six regions within Bangladesh. Predicted levels in poorest, least educated households were found to be twice as high as those in the richest and most educated with significant geographical variations reflecting differences in distribution of fuel use and house construction materials. Exposures for young children and poorly educated women were found to be fourfold higher than those for men in higher income households with educated women (range of 24-h average levels measured, ~133–638 $\mu g/m^3$ PM_{10})	Dasgupta *et al*. (2004a,b)
India	Systematic laboratory measurements of particulates and greenhouse gas emissions from 26 fuel/stove combinations used in conjunction with a rural fuel use database and information on stove use from the relevant Government Ministry to generate state-level information on biofuel use, stove use, extent of improved stoves and emissions from solid fuel use. The emissions inventory shows major contributions to greenhouse gas and health-damaging pollutants from biomass-burning stoves. (Although several determinants intervene between emission and exposure, total emissions are largely driven by fuel type similar to concentrations and exposures across states making secondary data on total emissions a useful proxy for population exposure).	Smith *et al*. (2000)
India	Quantitative measurement (of respirable particulate matter) results from a stratified sample of 420 households and determinant information from 1032 households identified fuel type, kitchen configuration, ventilation, age and gender to be the most important determinants of exposures in three districts of the southern state of Andhra Pradesh. Evaluation of the national improved stove programme across six states found little evidence of sustained use and maintenance following distribution. Reported stove use currently remains a poor proxy for potential exposure reductions (range of 24-h average levels measured, ~73–732 $\mu g/m^3$ PM_4).	World Bank (2002a, 2004a)

Table 1.23. (contd)

Country	Description of study results	Reference
India	Quantitative data from ESMAP study above used to generate district level concentration and exposure profiles based on distribution of fuel use, kitchen configuration, age and sex distribution for the state of Andhra Pradesh. District level distributions largely driven by differences in fuel use. Differences were relatively modest compared with the high average exposures estimated for each district (range of modelled 24-h weighted average estimates for the district, ~350–450 µg/m^3 PM$_4$).	Balakrishnan *et al.* (2004)
India	Information on quantities of biofuel used compiled from food consumption statistics and specific energy requirements for food cooking for all major states and regions of India. Total biofuel consumption was estimated (with significantly lower uncertainties than that previously estimated using energy surveys) at 379 Tg/year with a national average biofuel mix of 74:16:10 for fuel-wood, dung and crop residues respectively. North and eastern regions of the country show higher biofuel consumption together with high per-capita food consumption and higher prevalence of dung and crop residue use. (Since consumption is linked to emissions and emissions to exposures, this represents a new measure to judge exposure potential related to cooking with biomass).	Habib *et al.* (2004)
Sri Lanka	Questionnaire survey of 1720 households from three villages in Sri Lanka used to prepare a profile of gender and poverty dimensions of energy access. Approximately 96% of surveyed households used biomass with 42% using some form of improved stoves and 67% of all stoves having chimneys. About 79% had attached kitchens and ~20% had kitchens well separated from the main house.	Wickramsinghe (2005)

(ii) *Quantitative studies of exposure*

While domestic combustion of solid fuel generates a mixture of pollutants, because of limited technical feasibilities and difficult field logistics, most studies in the region have restricted themselves to cross-sectional measurements of single pollutants (most often PM and/or carbon monoxide). However, a few large-scale studies (that mostly measured fractions of PM) carried out in India, Nepal and Bangladesh across multiple exposure configurations have provided considerable understanding of spatial, temporal and other determinants of population exposure related to solid fuel use in the region. A few have also assessed levels of other gaseous pollutants including sulfur dioxide, nitrogen dioxide and select air toxics including PAHs and formaldehyde. Limited evidence is currently available to indicate (i) whether PM and carbon monoxide are representative indicator pollutants, (ii) whether the two are themselves consistently correlated under a wide range of exposure circumstances and (iii) how levels and proportions of other toxic constituents may vary with alternative distributions of determinants (most importantly with fuel type).

The following sections describe selected studies conducted within the region that measured levels of indoor air pollution to illustrate the scale and extent of exposures associated with the use of solid fuels for cooking and heating indoors. Several smaller studies have also been conducted, and, while an exhaustive listing of all studies conducted could not be compiled, Table 1.24 lists the major studies available in the published literature as well as in reports of projects available in the public domain. The global database of indoor air pollution studies maintained by the Department of Environmental Health Sciences, University of California Berkeley, USA (Saksena *et al.*, 2003; WHO, 2005a), the bibliography of indoor air pollution studies maintained by The Energy Research Institute, New Delhi, India, and independent articles retrieved through internet search engines served as the basis for this compilation.

(iii) *Measurement studies in India*

Quantitative measurement studies have been conducted in India since the early 1980s. Many of the earlier studies only measured TSP matter during short cooking periods. One of the earliest large-scale studies of exposure assessment was conducted in the households of Garhwal, Himalayas (Saksena *et al.*, 1992), and involved nearly 122 households in three villages across three seasons. Daily integrated exposure to TSP matter and carbon monoxide was assessed by personal and stationary sampling of air in six microenvironments. Concentrations of pollutants measured at the time of cooking were found to be very high (5.6 mg/m^3 and 21 ppm for TSP matter and carbon monoxide, respectively) but comparable with those measured in the Indian plains. The mean concentration in the kitchen while cooking often exceeded the concentration in other microenvironments, including the living rooms, and outdoors by an order of magnitude or more. Combining area measurements with individual time–activity records, the daily exposure of adult women to TSP matter and carbon monoxide was estimated to be 37 mg•h/m^3 and 110 µg•h/m^3, respectively.

More recently, two large-scale exposure assessment exercises for respirable particulates have been completed in India in the southern states of Tamil Nadu and Andhra Pradesh, respectively. In Tamil Nadu (Balakrishnan *et al.*, 2002), a total of 436 rural households across four districts were monitored for respirable particulates (median aerodynamic diameter, 4 µm). Concentrations were determined during several cooking and non-cooking sessions in households and 24-h exposures were calculated on the basis of these concentrations in conjunction with time–activity records of household members. Concentrations of respirable particulate matter ranged from 500 to 2000 µg/m^3 during cooking in households that used biomass (geometric mean [GM], 1043–1346 µg/m^3)

Table 1.24. Major studies with quantitative measurement results for indoor air pollution related to the use of solid fuel in South Asia

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Location[a]	Sampling duration[b]	Method	Range of levels reported (μg/m^3)[c]
Short-term exposure (<8 h)									
Aggarwal *et al.* (1982), India cited in GDB	5 urban homes		Wood	Traditional	TSP PAH (BaP)	Kitchen (1.5 m)	0.25 h (C)	Gravimetric TLC	7203 1270 (ng/m^3)
	4 urban homes		Dung	Traditional	TSP PAH (BaP)	Kitchen (1.5 m)	0.25 h (C)	Gravimetric TLC	15 966 8248 (ng/m^3)
	3 urban homes		Charcoal	Traditional	TSP PAH (BaP)	Kitchen (1.5 m)	0.25 h (C)	Gravimetric TLC	26 147 4207 (ng/m^3)
Smith *et al.* (1983), India	28 rural homes	Winter	Wood	Traditional	TSP BaP	Kitchen (breathing zone)	Meal duration	Gravimetric TLC	6400 4100 (ng/m^3)
	8 rural homes			Improved	TSP BaP			Gravimetric TLC	4600 2400 (ng/m^3)
Davidson *et al.* (1986), Nepal	18 rural homes	Winter	Wood	Traditional	TSP PM_{10}	Kitchen Kitchen	1–2 h (C) 1–2 h (C)	Gravimetric Gravimetric	880 (GM) 4700 (GM)
Reid *et al.* (1986), Nepal	60 rural homes	Autumn	Wood	Traditional Improved	TSP TSP	Personal exposures	1–2 h (C) 1–2 h (C)	Gravimetric Gravimetric	1750–3170 870–1370
Pandey *et al.* (1990), Nepal cited in GDB	20 rural homes at 1500 m	Summer	Wood/crop residue	Traditional	$PM_{2.5}$	Personal exposures	1 h (C)	Gravimetric	8200
				Improved	$PM_{2.5}$	Personal exposures	1 h (C)	Gravimetric	3000

Table 1.24 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Location[a]	Sampling duration[b]	Method	Range of levels reported (µg/m^3)[c]
Saksena *et al.* (1992), India	12 rural homes/6 micro-environments	Winter/ summer	Wood	Traditional	TSP CO	Personal exposures	Meal duration	Gravimetric TLC Electrochemical sensors	5600 21
Raiyani *et al.* (1993a), India	20 urban homes in each fuel category		Dung/wood/ charcoal	Traditional	TSP BaP	Kitchen (breathing zone)	Meal duration	Gravimetric TLC/HPLC	1190–3470 38–410 (ng/m^3)
Smith *et al.* (1994), India	61 urban homes		Wood/crop residue	Traditional	PM_{10}	Personal exposures	Meal duration	Gravimetric	900–1100
Smith *et al.* (1994), Bangkok	17 urban homes		Charcoal		PM_{10}	Personal exposures	Meal duration	Gravimetric	550
TERI (1995), India cited in GDB	20 homes with 18–20 measurements in each home		Wood	Traditional	PM_5	Kitchen (breathing zone)	Meal duration	Gravimetric	850–1460
Mandal *et al.* (1996), India cited in GDB	12 urban homes		Wood	Traditional	TSP	Kitchen (breathing zone)	4 h (C)	Gravimetric	646
Ellegard (1997), Viet Nam cited in GDB	35 urban homes		Wood		PM_{10}	Kitchen (breathing zone)	Meal duration	Gravimetric	770

Table 1.24 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Location[a]	Sampling duration[b]	Method	Range of levels reported (μg/m^3)[c]
Balakrishnan *et al.* (2002), India	436 rural homes from 4 districts stratified across four kitchen types	Summer	Wood/wood chips/crop residues	Traditional	PM_4	Personal exposures	1–2 h (C)	Gravimetric	1307–1535 (GM) (wood fuel)
						Living	2–4 h (C)		847–1327 (wood fuel)
Saksena *et al.* (2003)	40 urban homes		Wood	Traditional	PM_5	Kitchen (breathing zone)	Meal duration	Gravimetric	1200
Bhargava *et al.* (2004), India	10 rural homes	Summer/ winter	Wood	Traditional	BaP	Kitchen (1.5 m) (C)	1 h	HPLC	700–1700 ng/m^3
			Dung						980–1860 ng/m^3
Long-term exposure (8–24 h)									
Hessen *et al.* (1996), Nepal	34 rural homes		Wood	Traditional	TSP	Kitchen	24 h	Gravimetric	8420
Yadav *et al.* (1996), Nepal cited in GDB	39 rural homes at 2500 m	Winter	Wood	Traditional	TSP	Kitchen	8 h	Gravimetric	6400
				Improved	TSP	Kitchen	8 h	Gravimetric	4600
Balakrishnan *et al.* (2002), India	436 rural homes from 4 districts stratified across four kitchen types	Summer	Wood/wood chips/crop residues	Traditional	PM_4	Personal exposures	24 h	Gravimetric	172–226

Table 1.24 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Location[a]	Sampling duration[b]	Method	Range of levels reported (µg/m^3)[c]
Balakrishnan *et al.* (2004), India	412 rural homes from 3 districts stratified across four kitchen types	Summer	Wood/dung/ crop residues	Traditional	PM_4	Personal exposures	22–24 h	Gravimetric and direct read out	431–467
						Kitchen			297–666
						Living			215–357
Dasgupta *et al.* (2004a,b), Bangladesh	236 rural homes	Summer	Wood, dung, crop residues	Traditional	PM_{10}	Personal exposures	22–24 h	Gravimetric and direct read out	196–264
						Kitchen/living			60–1165

BaP, benzo[*a*]pyrene; CO, carbon monoxide; GM, geometric mean; HPLC, high-pressure liquid chromatography; PAH, polycyclic aromatic hydrocarbons; $PM_{2.5}$, particulate matter <2.5 µm; PM_4, particulate matter of 4 µm; PM_5, particulate matter of 5 µm; PM_{10}, particulate matter <10 µm; TLC, thin-layer chromatography; TSP, total suspended particulate matter

[a] Personal exposures usually refer to exposures of cooks.

[b] C denotes sampling during cooking. Meal duration refers to the sampling duration that covers the cooking period and typically ranges from 1 to 2 h.

[c] Most studies report arithmetic means unless otherwise specified. Distributions of levels have been found to be skewed in many studies but few report geometric means.

and average 24-h exposures ranged from 90±21 μg/m^3 for those not involved in cooking to 231±109 μg/m^3 for those who cooked; 24-h exposures were around 82±39 μg/m^3 in households that used clean fuels (with similar exposures across household subgroups).

The study in Andhra Pradesh (World Bank, 2002b; Balakrishnan *et al.*, 2004) quantified daily average concentrations of respirable particulates (median aerodynamic diameter, 4 μm) in 412 rural homes from three of its districts and recorded time–activity data from 1400 household members. Mean 24-h average concentrations ranged from 73 to 732 μg/m^3 (GM, 61–470 μg/m^3) in households that used gas versus solid fuel, respectively. Concentrations were significantly correlated with fuel/kitchen type and quantity of fuel. Mean 24-h average exposures ranged from 80 μg/m^3 to 573 μg/m^3 among users of solid fuel. Mean 24-h average exposures were the highest for women cooks (GM, 317 μg/m^3) and were significantly different from those for men (GM, 170 μg/m^3) and children (GM, 184 μg/m^3). Among women, exposures were highest between the ages of 15 and 40 years (most likely to be involved in cooking or helping to cook), while among men, exposures were highest between the ages of 65 and 80 years (most likely to be indoors). The exposures were also characterized by dramatic temporal differences between cooking and non-cooking periods. Large peaks in concentrations during cooking accounted for most of the exposure potentials. Fuel type, type and location of the kitchen and the time spent near the kitchen while cooking were thus the most important determinants of exposure across these households in southern India among the other parameters examined that included stove type, cooking duration and smoke from neighbourhood cooking.

A few measurements of particulate size fractions have also been made in households that use biomass and coal (Aggarwal *et al.*, 1982; Raiyani *et al.*, 1993a). In these studies, which were carried out in households of peri-urban Gujarat (in western India) and measured TSPs (using a cascade impactor) during cooking, the proportion of particles less than 9 μm in aerodynamic diameter was estimated to be 96% (dung), 86% (wood) and 92% (coal). Dung use also gave the highest proportion of particles less than 2 μm in aerodynamic diameter (80%), followed by coal (70%) and wood (47%).

Finally, a few studies have measured emissions, area concentrations and size distributions of volatile and semi-volatile particle-bound PAHs released during solid fuel combustion. Personal exposure concentrations of benzo[*a*]pyrene measured over 15–30-min average sampling periods (in 15 urban households in western India) during wood and dung-cake combustion ranged from 1.30 to 9.30 μg/m^3 (Aggarwal *et al.*, 1982). In another study in northern India (Bhargava *et al.*, 2004), personal exposure and area measurements for PAHs were made during the cooking period in 20 households over two seasons. Concentrations of total PAHs in the respirable particulate fraction ranged from 4.5 to 33.5 μg/m^3. Personal exposure concentrations for cooks who used biofuels were significantly higher than corresponding area concentrations. Personal exposure concentrations during cooking were nearly an order of magnitude higher than those during other periods. Both concentrations were also higher in winter than in summer.

Area concentrations of 16 particulate PAHs measured over a cooking period of 45–60 min (five for each category of fuel; in households from a peri-urban cluster in western India) were 2.01, 3.46 and 3.56 μg/m^3, respectively, from wood, wood/dung-cake and dung-cake combustion (Raiyani *et al.*, 1993b). Particulate PAH size distributions measured in these same indoor environments showed that houses that used cattle dung, wood and coal had 96%, 80% and 76% of the PAH mass, respectively, contained in particulates of ~ <2 μm aerodynamic diameter (Raiyani *et al.*, 1993a). There was a predominance of benzo[*a*]pyrene (20%) and dibenz[*a*,*h*]anthracene (25%) and of chrysene (10%) and benzo[*a*]pyrene (13%), respectively, in particles from wood and dung-cake combustion. Laboratory emission studies for PAHs (Venkataraman *et al.*, 2002) that used wood, dung cakes and biofuel briquettes in traditional and improved stoves have shown that dung-cake and briquette fuels are significantly more polluting than wood in terms of total emissions. The PAH profiles showed a predominance of fluoranthene, pyrene and benz[*a*]anthracene from all biofuels. The PAH size distributions from all stove–fuel systems were unimodal with mass median aerodynamic diameters in the 0.40–1.01 μm range for both semivolatile and nonvolatile PAHs.

(iv) *Measurement studies in Nepal*

While most studies within the region have been conducted in India and give a reasonably representative picture of pollution levels experienced in the area, a few studies conducted in Nepal illustrate the exposure situation in cold, hilly regions where solid fuels are used for cooking as well as heating. Ecological and climatic conditions play a central role in fuel choices and quantities, with associated implications for exposure. Earlier studies conducted in the 1980s (Davidson *et al.*, 1986) reported stove use for cooking and heating in Nepali households to average 11.6 h per day, with additional use of a fireplace or nearly all-day operation of stoves for heating in many instances (in comparison, the average duration of stove use in the region without heating needs is estimated at 2.9 h per day). Correspondingly, fuel quantities used and time spent for fuel collection were higher (8.2 kg per day at high elevations and 2.8 kg per day in the lower elevations for 7.7 h per day, compared with an average of 1.9 kg per day for 0.5 h per day in Indian households at lower elevations during the same period). Levels of TSPs were in the range of 3–42 mg/m^3, with respirable suspended particles in the range 1–14 mg/m^3 in the houses sampled. Concentrations of potassium and methyl chloride (indicators for biomass sources) in outdoor air indicated significant contributions from indoor sources to outdoor air pollution in the area as well.

More recently, results from measurements of TSP matter, PM$_{2.5}$ and carbon monoxide have been reported (Reid *et al.*, 1986; Pandey *et al.*, 1990) in homes that used solid fuels in traditional and improved stoves. Use of improved stoves resulted in a two- to threefold reduction in cooking period concentrations of total TSP matter, PM$_{2.5}$ and carbon monoxide. Values for TSP matter in traditional stoves ranged from 1750 to 3170 μg/m^3 compared with 870 to 1370 μg/m^3 for improved stoves; mean values for PM$_{2.5}$ were 8200 μg/m^3 compared with 3000 μg/m^3 for improved stoves; and mean values for carbon monoxide ranged from 64 to 310 μg/m^3 compared with 41 to 80 μg/m^3 for improved stoves. This finding is similar to that reported in other regions with improved stoves (e.g. in Guatemala, Kenya), where, despite being substantially lowered, the concentrations remain considerably higher than levels in households that used gaseous fuels as well as common health-based guideline values.

(v) *Measurements in Bangladesh*

Until recently, few measurement results had been reported from Bangladesh. A recent study conducted by the World Bank (Dasgupta *et al.*, 2004a,b) now provides a substantial amount of information on the levels and distribution of pollutants across a very large number of exposure configurations. Using methods similar in nature to recent large-scale assessments in southern India, a stratified sample of 236 households was monitored using direct read-out and traditional gravimetric methods for particulates for periods of 22–24 h. Households were stratified on the basis of fuel, kitchen location and housing materials. Across households, 24-h average PM_{10} concentrations varied from 84 to 1165 μg/m^3 for firewood, 60 to 755 μg/m^3 for dung and 72 to 727 μg/m^3 for jute. Many houses reported fairly low levels during parts of the night and afternoon, when indoor readings resembled ambient readings. However, differences in cooking practices, structural arrangements and ventilation made a significant impact on overall concentrations. While most houses that used biomass reported high PM_{10} levels, a few were similar to households that used cleaner fuels such as LPG or natural gas, which suggests that ventilation is an important factor in reducing pollution levels. Improved stove use was found to be minimal which is similar to the situation found in the Indian studies. Exposure reconstructions using time–activity records in conjunction with area measurements confirmed observations from other studies of the region. Women in all age groups and children under the age of 5 years of both sexes in homes that used biomass faced the highest exposures compared with men in the working age group (24-h exposure concentrations of PM_{10} for women ranged from 209 to 264 μg/m^3 and for children from 156 to 209 μg/m^3 compared with 118 μg/m^3 for men in the age group of 20–60 years). Time spent outdoors was a major contributor to reduced exposures, as reflected by much lower exposures for adult men who spend a considerable fraction of the day outdoors. The study developed regression models that used the measurement results in conjunction with survey information on household level determinants and socioeconomic variables to create a basis for extrapolation to six regions within the country. Significant geographical differences were found, based: directly—on differential distribution of determinants including fuel choice, household ventilation and materials used for construction; and indirectly—on income, education and demographic variables through their effects on choice of fuel and prevalent household conditions.

(b) Conclusions and recommendations for further research

Exposure to indoor air pollutants associated with the combustion of solid fuels for cooking and heating is extensive in South Asia. Multiple determinants affect individual exposures but it is clear that all users of solid fuel experience very high air pollution leading to exposure to a mixture of pollutants for extended periods during their lifetime.

Exposures are widespread and prevalent in half to three-quarters of the population in most countries of the region. Although evidence of extreme exposures has been available in the published literature for the last three decades, only recently have countries in the region undertaken efforts to collect information systematically on the extent of solid fuel use and estimated exposures. Despite limitations of being outside regulatory purviews and hence not being within a framework for consistent and routine data collection, the region has a robust series of research studies to document evidence of exposures. While quantitative assessments have been performed in many countries, a great majority focused on a few pollutants (such as PM and carbon monoxide) and showed limited evidence of their correlation to other toxic emissions; it would therefore be important for future research studies to undertake measurements of multiple pollutants. Additional measurements of carcinogenic compounds in biomass smoke are especially needed as very little is currently available in the region. Models that validate the choice of indicator pollutants and monitoring schemes that adequately describe the temporal and spatial variations are also urgently needed. Since most countries in the region have not yet developed specific standards, such models would facilitate guidance on what, when, where and how to monitor issues that duly take into account the technical and financial feasibilities of individual countries.

Women and children probably bear the largest burden of health risks from these exposures. Poverty, income and education are likely to aggravate further exposure potentials for vulnerable groups. Within the context of the Millennium Development Goals, it would be pertinent and almost necessary to identify and include indoor air pollution issues as an integral part of addressing the health problems of women and children in all countries. Indeed, if the region is to progress towards achieving even moderate human development indices within the next decades, indoor air pollution will probably be an important category of environmental risk factors in need of solutions.

1.3.4 *Latin America*

(a) Use of fuels

In Latin America, biomass fuels are mostly used in rural areas. Nearly 25% of the population of Latin America lives in rural areas where biomass fuels are most frequently used for cooking and heating. This rural population represents nearly 127 million people who are potentially exposed to biomass-related air pollution (Cordeu & Cerda, 2000). The percentage of the rural population varies from country to country and can be as high as 60%, for example in Guatemala. In Mexico, nearly 25 million people use biomass, particularly wood, as a primary source of energy for daily cooking. This number will probably remain similar or increase in the near future, since most rural families do not have the possibility of using a fuel that would be higher in the ‘energy ladder’ such as gas or electricity. A study conducted in Central America that included Guatemala, Honduras and El Salvador concluded that 95% of the rural households used wood burning as a source of energy for cooking (Organización Latinoamerica de Energía, 2000). Using data from local estimates, surveys and some demographic and development indicators, Smith *et al.* (2004) built a model to predict the national use of solid fuels. For Latin America, those estimates were 24.6% (18.8–30.8%) for Mexico and Brazil and 52.9% (42.6–63.2%) for Ecuador.

In general, there is an inverse correlation between the size of the locality and the use of biomass; the smaller and most disperse communities are those that use biomass fuel most extensively (Riojas, 2003). In rural communities in Mexico, it has been estimated that the mean quantity of wood used per person per day is approximately 3 kg. For a typical family, consumption per year is equivalent to 4 tonnes of wood (Riojas, 2003).

(b) Exposure data

Several factors affect the concentration of pollutants within the household during the burning of open fires, in particular the volume and ventilation of the room, and the intensity of the fire. Climatic conditions are major determinants of exposure and are particularly important in some Latin American countries (e.g. Bolivia, Ecuador or Peru) where a large proportion of the rural population lives at high altitude. In addition, the type of cooking will also have an impact on exposure. Data from Mexico show that women can spend nearly 6–7 h per day close to biomass open-fire cooking (Brauer *et al.*, 1996).

Most of the studies that measured pollutant concentrations were conducted in rural settings and attempted to characterize the distribution of levels in the kitchen. Cooking times for meals varied from study to study and ranged from 30 min to 3 h. However, time spent close to a burning fire can reach up to 12 h. The highest exposure occurs among women and their young children; however, other members of the households are also exposed because, in many cases, the kitchen is not a separate room or meals are eaten near the stove (Naeher *et al.*, 2005).

(i) *Qualitative data*

In a study conducted in Guatemala, PM_{10} levels close to 1000 $\mu g/m^3$ or higher were observed in homes that used open fires and those of carbon monoxide were about 5–10 ppm and reached 25–50 ppm during use of the fire (Boy *et al.*, 2002).

(ii) *Quantitative studies*

Table 1.25 presents results from studies conducted in Latin America, mostly in Guatemala and Mexico, on pollutant concentrations in households that use biomass fuel.

Studies in Guatemala

Several studies have compared different types of indoor cookstove conditions to determine the potential impact of intervention. Naeher *et al.* (2000a,b) determined particulate and carbon monoxide concentrations in highland Guatemala and compared different cookstove conditions: background (no stove use), traditional open stove, improved stove (plancha) and bottled gas (LPG) stove. Measurements were taken for

Table 1.25. Concentrations of pollutants in selected studies on the use of biomass fuel conducted in Latin America

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (μg/m^3 for PM, mg/m^3 [ppm] for gases)
Naeher *et al.* (2000a), indoor air, western highland of Guatemala, Quetzaltenango, 2500–2800 m	9	Fall Rainy season	Wood	Open fire	Average CO	Kitchen	22 h	Drager CO	5.9 ppm
				Plancha					1.3 ppm
				LPG/open fire					1.3 ppm
				Open fire	Average $PM_{2.5}$	Kitchen		Gravimetry (SKC Universal Flow sample pump)	527.9
				Plancha					96.5
				LPG/open fire					56.8
				Open fire	Average PM_{10}	Kitchen		Gravimetry	717.1
				Plancha					186.3
				LPG/open fire					210.2
				Open fire	Average CO	Personal monitoring mother	10–12 h	Drager CO passive difusion	6.7
				Plancha					2.4
				LPG/open fire					1.5
				Open fire	Average $PM_{2.5}$	Personal monitoring mother		Gravimetry	481.2
				Plancha					257.2
				LPG/open fire					135.6
				Open fire	Average CO	Personal monitoring child		Drager CO passive difusion	2.7
				Plancha					1.9
				LPG/open fire					2.0
					Average $PM_{2.5}$	Personal monitoring child		Gravimetry	279.1
									169.7
									148.5

Table 1.25 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported ($\mu g/m^3$ for PM, mg/m^3 [ppm] for gases)
Albalak *et al.* (2001), western highland of Guatemala, La Victoria rural community in San Juan Ostuncalco, 2000–2300 m	30	Dry season Part of rainy season	Wood	Open fire Plancha LPG/open fire	$PM_{3.5}$	Kitchen	24 h average (women spent 5 h/day)	SKC Aircheck samplers Gravimetry	1560 (GM) 280 (GM) 850 (GM)
Naeher *et al.* (2001), western highland of Guatemala, Quetzaltenango, 2500–2800 m[a]	15 open fire 25 improved stove	Summer (rainy season)	Wood	Open fire Plancha	CO	Kitchen	24 h	Stain tube	4.0–22.7 0.0–7.1
				Open fire Plancha	$PM_{2.5}$	Kitchen	24-h	Gravimetric	324–2198 33–409
Bruce *et al.* (2004), Guatemala, western highland, La Victoria	29	Dry winter season	50% open fire 30% chimney stoves (plancha) 20% combination gas/open fires Wood, agricultural residues	Open fire Plancha	CO	Kitchen	24-h	Gas diffusion tubes	12.4 (10.2–14.5) 3.09 (1.87–4.30)
				Open fire (11) Plancha (5) Gas/other (8)	$PM_{3.5}$			Gravimetry	1019 (SD, 547) 351 (SD, 333) 579 (SD, 205)

Table 1.25 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported ($\mu g/m^3$ for PM, mg/m^3 [ppm] for gases)
Brauer *et al.* (1996), Mexico, San Jose Solis, 2450 m	22 homes	April–May Dry season	Biomass (corn stalks and husks)	Open fire	Average $PM_{2.5}$	Kitchen	9 h	Gravimetry	
						Biomass			554.7 (SD,492.9)
						Biomass+LPG			203.6 (SD, 180.6)
			Wood and LPG			LPG			69.4 (SD, 54.2)
				LPG	PM_{10}	Biomass			767.9 (SD, 540.5)
						Biomass+LPG			311.2 (SD, 247.8)
						LPG			225.5 (SD, 260.8)
Riojas-Rodriguez *et al.* (2001), Mexico	38	Dry season	Wood	Ceta stove and open fire	Average PM_{10}	Kitchen	16 h	Gravimetry	
						Cooking area			
						Stove			230
						Open fire			265
						Children area			
						Stove			233
						Open fire			202
		Rainy season				Cooking area			
						Stove			206
						Open fire			287
						Children area			
						Stove			158
						Open fire			305
Regalado *et al.* (2006), Mexico	*n*=778 samples		Biomass cooking fuel	Wood stove 12% with chimney	PM_{10}	Kitchen while cooking	1 h during cooking	Nephelometer	690 average 1390 peak
					$PM_{2.5}$				490 average 1040 peak

Table 1.25 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (µg/m^3 for PM, mg/m^3 [ppm] for gases)
Zuk *et al*. (2007), Mexico, rural Michoàcan, 2600 m	53	Winter Nov to January	Wood	Open stove	$PM_{2.5}$	Near stove	48 h	Gravimetric	693 (246–1338)
						In kitchen			658 (67–1448)
						On patio			94 (36–236)
				Patsari (improved stove)		Near stove			246 (63–614)
						In kitchen			255 (59–864)
						On patio			92 (51–295)
Hamada *et al*. (1991), Brazil, rural southern Brazil, 930 m	28 wood stoves	Winter	Wood	Closed stove with flues	DBA	Kitchen	24 h	HPLC/spectro-fluorometer	9.79 [ng/m^3]
					BaP				36.2 [ng/m^3]
					SPM			Gravimetry	108 µg/m^3
					NO_2	Kitchen	24 h		14.6 [ppb]
						Personal			9.0 [ppb]
Caceres *et al*. (2001), Chile, urban Santiago	24	Winter	Coal		PM_{10}	Kitchen	24 h	Gravimetric	250
					CO				42
					SO_2			Real-time portable monitor	192 ppb
			Firewood		PM_{10}				489
					CO				57
					SO_2				295 ppb

Table 1.25 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (µg/m^3 for PM, mg/m^3 [ppm] for gases)
Albalak *et al.* (1999), Bolivia, Altiplano, 4100 m	24 *n*=621 samples	January to October	Biomass fuel	Open fire	PM_{10}	*Kitchen*	6 h during cooking period in the morning	Gravimetry	
						Indoor cooking			1830 (SD, 2990)
						Outdoor cooking			430 (SD, 140)
						Home			
						Indoor cooking			280 (SD, 330)
						Outdoor cooking			840 (SD, 400)

[a] This study also reports results presented in Naeher *et al.* (2000a).

BaP, benzo[*a*]pyrene; CO, carbon monoxide; DBA, dibenzanthracene; GM, geometric mean; HPLC, high-pressure liquid chromatography; LPG, liquid petroleum gas; NO_2, nitrogen dioxide; PM, particulate matter; SD, standard deviation; SO_2, sulfur dioxide; SPM, suspended particulate matter

22 hour during the rainy season in nine houses. Background kitchen $PM_{2.5}$ levels were 56 μg/m^3; levels were 528 μg/m^3 for open fires, 97 μg/m^3 for planchas and 57 μg/m^3 for gas stoves. Similar trends were observed for personal exposures of mothers and children. However, the authors mentioned that improved stoves (planchas) deteriorate over time and that maintenance is important to control indoor pollutant levels. In a similar study, the same authors collected samples from 15 homes that used open fires and 25 homes that had improved stoves and reported concentrations similar to those of the first study (Naeher *et al.*, 2001). In another study conducted in the western highlands of Guatemala, 24-h $PM_{3.5}$ concentrations were monitored over 8 months for three fuel/cookstove combinations (10 in each category): a traditional open-fire cookstove, an improved cookstove called 'plancha mejorada' and LPG stove/open-fire combination for which mean levels were reported to be 1560 μg/m^3, 280 μg/m^3 and 850 μg/m^3, respectively (Albalak *et al.*, 2001). Similar orders of magnitude of $PM_{3.5}$ levels were observed in the study of Bruce *et al.* (2004).

Studies in Mexico

A follow-up study in two rural communities of the state of Chiapas, Mexico, compared families who used an improved stove for cooking with those who used traditional open fires. Measurements (16-h) of PM_{10} showed that the concentration of particles was significantly lower in the kitchen area (158 μg/m^3 versus 233 μg/m^3) during the rainy season compared with the dry season (Riojas-Rodríguez *et al.*, 2001). Two studies conducted in Mexico evaluated the impact of the use of biomass on the respiratory health of women. In a case–control study, 127 cases with chronic bronchitis or chronic airway obstruction and 280 controls were recruited at the National Institute of Respiratory Disease in Mexico (Pérez-Padilla *et al.*, 1996). Cases reported a mean of 3 h of cooking with a wood stove per day and a range from none to 12 h. The mean duration of cooking with a wood stove was 28 years and ranged from none to 71 years. It was calculated that the h•year value of exposure (years of exposure multiplied by the average number of hours of exposure per day) was 80 (mean) and values ranged from 0 to 552 h•years. No objective measurement of particle levels was carried out; however, measurements taken in rural Mexico showed average levels of $PM_{2.5}$ of 555 μg/m^3 (range, 30–1492 μg/m^3) when biomass was burned in open fires (Brauer *et al.*, 1996). Using an integrated nephelometer during 1 h of cooking time, levels of exposure to $PM_{2.5}$ measured in homes with stoves with (and without) a chimney averaged 490 (SD, 610) μg/m^3 with a peak of 1040 (SD, 1010) μg/m^3 (Regalado *et al.*, 2006).

As part of a large health intervention study, Zuk *et al.* (2007) evaluated the impact of improved wood burning stoves on indoor air pollution in 52 homes in the rural town of Michoacan, Mexico, and monitored levels before and after the improved wood-burning stoves were received. Mean $PM_{2.5}$ concentrations (48-h) in homes that burned wood in open fires were 693 μg/m^3 near the stove and 658 μg/m^3 in the kitchen away from the stove. Paired measurements taken before and after installation of the patsari (improved stove) indicated a median 71% reduction in $PM_{2.5}$ concentrations near the stove and a 58% reduction in the kitchen concentration.

Studies in other Latin American countries

In a study conducted in a rural community of southern Brazil during the winter, concentrations of PAHs and suspended particulate matter were assessed in homes that used wood and gas stoves. Higher levels of PAHs and suspended particulate matter were observed in homes that used wood stoves (Hamada *et al.*, 1991).

Indoor air pollution was also measured in 24 houses in an area of low socioeconomic status in Santiago, Chile. The highest concentrations of PM_{10}, carbon monoxide and sulfur dioxide were measured during the time of heating with higher levels observed for firewood burning than coal. Coal, firewood and cigarette smoke were all sources of carcinogenic PAHs (Cáceres *et al.*, 2001).

In a study conducted in a rural village of the Bolivian altiplano located at 4100 m above sea level, PM_{10} levels were measured in a total of 621 samples. In homes in which cooking was carried out indoors, the mean PM_{10} concentration in kitchens was 1830 $\mu g/m^3$ and ranged from 580 to 15 040 $\mu g/m^3$ over a 6-h cooking period. Daily exposure for women involved in indoor cooking was 11 280 $\mu g•h/m^3$ during the working season (harvesting and planting season) and 15 120 $\mu g•h/m^3$ during the non-work season (Albalak *et al.*, 1999).

(iii) *Intervention studies*

Several intervention studies have shown the impact of improved stoves or installation of hoods or chimneys on exposure levels. Studies conducted in Guatemala showed that, compared with open fires alone, the LPG/open fire combination showed a 45% reduction in $PM_{3.5}$ ($p<0.07$) while the plancha mejorada showed a 85% reduction in $PM_{3.5}$ concentration compared with open fires ($p<0.0001$). Season did not affect pollutant concentration and the reduction of $PM_{3.5}$ was maintained throughout the 8 months of the study (Albalak *et al.*, 2001). Bruce *et al.* (2004) reported an almost 65% reduction in indoor $PM_{3.5}$ levels with improved stoves. Similarly, a study conducted in Mexico showed that improved stoves could provide a median 71% reduction in $PM_{2.5}$ concentration near the stove and a 58% reduction in the kitchen (Zuk *et al.*, 2007).

1.3.5 *Africa* (Table 1.26)

(a) Indoor air and personal exposure data

The percentage of households that use solid fuel in African has been estimated to be approximately 73% (68–78%) in Saharan Africa and 86% (81–89%) in sub-Saharan Africa (Smith *et al.*, 2004*)*. Studies from Africa have mainly been carried out in Kenya, The Gambia and South Africa. Daily measurements of PM_{10} usually exceeded 1500 $\mu g/m^3$ (Saksena & Smith, 2003). Recent data from Zimbabwe showed that women spend on average 5 h per day in the kitchen area and that the levels of PM_{10} were in the

Table 1.26. Concentrations of pollutants in selected studies on the use of biomass fuel conducted in Africa

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (μg/m^3 for PM, mg/m^3 [ppm] for gases)
Cleary & Blackburn (1968), New Guinea	9	Not reported	Wood	Not reported	Smoke density, aldehydes, CO	Native huts, new Guinea highlands	Different times for each hut described	Brass filter holder, hand pumps	666 (average) 1.08 ppm (average) 3.8 ppm (peak)
					CO				21.3 ppm (average) 150 ppm (peak)
WHO/UNEP (1988), The Gambia		Dry and rainy seasons	Wood		24-h SPM		14 h		2000 (GM) dry 2100 (GM) rainy
Boleij *et al.* (1989), Kenya	36 randomly selected from 250 in area	Rainy season (April, May)	Mostly wood sometimes biomass fuels (agricultural waste)	Traditional 3-stone open fire within house (58%), or in separate kitchen (42%)	Respirable particles NO_2	Rural area of Maragua, Kenya; kitchens	7 h/day (fire burning) Measurements 24 h average	Pump (Dupont P2500) and PAS-6 filter holder with glass fibre filters	1400 (mean) 180 (mean)
Collings *et al.* (1990), Zimbabwe	40	Spring	Wood, paraffin, gas, electricity	Mostly open fires in thatched huts.	PM	Kitchen	2 h	Casella 3131 TT personal sampler with Whatman 42 filter paper. EEL Densitometer No. 19	546 and 1998

Table 1.26 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (µg/m^3 for PM, mg/m^3 [ppm] for gases)
Terblanche *et al*. (1992), South Africa			Biomass, tobacco, outdoor pollution		Median TSP		12.1 h		310 (school day) 298 (holiday)
Ellegard & Egneus (1993), Lusaka, Zambia	268 housewives	Not reported	Wood, charcoal, electricity	Wood Charcoal Electricity	Mean respirable particles <7.1 µm	Personal sample	2.5 h cooking time; 4-5 h monitoring time	Air pumps (Gil-Air) with cyclone, Millipore SCWP 03700 filter, Drager colorimetric diffusion tubes	890 380 240
Gachanja & Worsfold (1993), Kenya	9		Biomass fuels, wood, charcoal, dung, crop residues	Compared 2 charcoal burning stoves – traditional 3-stone and ceramic-lined	Total PAH Chrysene, benzo[*a*]anthracene, benzo[*a*]pyrene, benzo[*ghi*]perylene, 3-methylcholanthrene	Kenya highlands; kitchens	2–4 h	Glass microfibre filter and XAD-2 resin cartridge	2.6 (max.) 1–540 [ng/m^3] (range)

Table 1.26 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (µg/m^3 for PM, mg/m^3 [ppm] for gases)
Ellegard (1994), Zambia	Not reported	March	Wood, charcoal, electricity	Wood Charcoal Electricity Charcoal producer	Mean TSP (respirable suspended particulates)	Kamaila, Chisamba, Zambia	4.7 h 4.8 h 4.5 h 2.3 h	Air pumps (Gil-Air SC) fitted with filter & cyclone	890 380 240 1400
Campbell (1997), The Gambia	18 (6 in each of 3 villages)	Over 12 months, dry and wet season	Biomass fuels (wood, dung, crop residues)	Not reported	TSP Benzo[*ghi*]-perylene Pyrene Benzo[*a*]-anthracene (particulates, NO_2, PAH)	2 Mandika villages, 1 Fula hamlet; kitchens	24 h	Boleij *et al.* (1988a,b)	2000 (mean) 246 [µg/g] (AM) 160 [µg/g] (AM) 147 [µg/g] (AM)
Ellegard (1997), Maputo	1000	Not reported	Mainly wood and charcoal; less common: electricity, LPG, kerosene, coal	Wood Charcoal Electricity LPG Kerosene Coal	Mean respirable particulates	10 suburban bairros around Maputo; cooking place varied.	2.84 h per day; monitoring period equal to actual cooking time (av 1.5h)	Air pumps (Gil-Air SC) with cyclone. Diffusion tube (Drager 6733191)	1200 540 380 200 760 940

Table 1.26 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (µg/m^3 for PM, mg/m^3 [ppm] for gases)
Bailie *et al.* (1999)	75	Winter	Paraffin and electricity most common; gas and wood less common	Not reported	TSP	Poor urban environment	Includes peak fuel use periods	Electrochemical Exotox Model 75 continous monitors, Gil-Air model 224-XR pumps	7.15–432 continuous daily monitoring
Ezzati *et al.* (2000), Kenya	55	–	Wood, dung, charcoal	Wood Charcoal	Average daily PM$_{10}$		14 h/day, >200 days	Personal data RAM nephelometer	2795–4898
Sanyal & Madunaa (2000), South Africa	115	3 times: June-Sept, Oct-Dec, Mar-May	Wood, dung, coal	Very low income Low income Middle income	CO	Residential area of Victoria East; cooking and living areas	6 h (morning and afternoon)	EXOTOX Model 75 continuous gas monitors	180 118 67

Table 1.26 (contd)

Reference, location	No. of households	Season	Fuel	Stove type	Pollutant	Area	Average time	Method	Range of levels reported (µg/m^3 for PM, mg/m^3 [ppm] for gases)
ITDG (2002), West Kenya and Kajiado	50	2 rounds – wet and dry season	Wood, residues, biomass, kerosene	Before intervention	PM and CO	West Kenya	3.8	Air sampler, stain tubes	1713 (PM), 10.1 (CO)
						Kajiado	2.5		5526 (PM), 74.7 (CO)
	50	2 rounds – wet and dry season		After intervention	PM and CO	West Kenya	3.14	Air sampler, stain tubes	628.9 (PM), 4.7 (CO)
						Kajiado	1.52		3522.4 (PM), 51.4 (CO)
				Wood	Mean CO				8.5
				Charcoal					13
				Electricity					2.1
Mishra *et al.* (2004), Zimbabwe	150	15 August – 30 Nov	Wood, dung, charcoal, electricity, LPG, kerosene	Unvented cook stoves	CO	Zimbabwe, 10 provinces; kitchen	5 h	–	300–1000 (range)
					PM_{10}				1000–4000 (range)
Röllin *et al.* (2004), South Africa	105	Summer	Wood, paraffin (kerosene), electricity	With/without chimney	PM	South African rural villages, North-West Province; kitchen and on-person	24 h	Pumps with cyclones, Drager passive diffusion tubes	Unelectrified areas: median, 107; electrified areas: median, 37.5

CO, carbon monoxide; GM, geometric mean; LPG, liquid petroleum gas; NO_2, nitrogen dioxide; PAH, polycyclic aromatic hydrocarbons; PM, particulate matter; SO_2, sulfur dioxide; SPM, suspended particulate matter; TSP, total suspended particulates range of 1000–4000 μg/m^3 and those of carbon monoxide were in the range of 300–1000 ppm (Mishra *et al.*, 2004).

A study conducted in The Gambia, where combustion of biofuels is predominantly related to cooking fires, reported a mean level of suspended particulate matter (24-h average) of 2000 μg/m^3 with a range of 675–3444 μg/m^3. High concentrations of PAHs were also seen, with a mean level of benzo[*a*]pyrene of 102 ng/m^3 that ranged from 69 to 351 ng/m^3 and a mean level of dibenzo[*a*,*h*]anthracene of 149 ng/m^3 that ranged from 101 to 513 ng/m^3 (Campbell, 1997). Data from Kenya also reported high particulate levels during home cooking on three traditional stone open fires (using mostly wood). Fires were burning for almost 7 h per day. Average levels of suspended particulate (24-h) were approximately 1400 μg/m^3 (SD, 1000). PAHs were also measured; average levels of benzo[*a*]pyrene on filters were 60 μg/m^3 (SD, 50) and those of dibenz[*a*,*h*]anthracene were 100 μg/m^3 (SD, 90) (Boleij *et al.*, 1989).

Indoor concentrations of 12 PAHs were measured in Burundi in 16 rural houses that used traditional wood stoves. In addition, 32 residents of these homes provided data on urinary excretion of 1-hydroxypyrene. Mean airborne concentrations of four volatile PAHs (naphthalene, fluorene, phenanthrene and acenaphthene) exceeded 1 μg/m^3 and that of benzo[*a*]pyrene was 0.07 μg/m^3. Naphthalene was the main PAH contaminant. Mean urinary 1-hydroxypyrene excretion of residents of traditional houses was 1.50 μmol/mol creatinine (range, 0.26–15.62 μmol/mol), a value that was 30 times higher than that of people who lived in the capital city of Burundi (Viau *et al.*, 2000).

In a study conducted in Kenya, personal exposure from biomass burning in a rural population was determined using data on type of activity, emission concentrations, time spent in different microenvironments and proximity to the fire during the burning period. Because exposure to biomass burning varies from day to day (depending on the moisture content or density of the fuel, the type of food cooked, the choice of stove and fuel) and from season to season (different activity pattern, ventilation of the home), a detailed exposure measurement was made over several days (200 days) and seasons. Exposure was higher for women than men, but was similar in children of either sex under 5 years of age. The highest exposure was observed in women aged 15–49 years and reached 4.9 mg/m^3 per day (Ezzati & Kammen, 2001).

In a study conducted in Zambia, personal exposure to respirable particles (<7.1 μm) was measured in housewives exposed to different types of fuel during cooking time. Women exposed to emissions from wood burning had the highest level (890 μg/m^3) compared with those who used charcoal (380 μg/m^3) or electricity (240 μg/m^3) (Ellegard & Egneus, 1993).

(b) Impact of intervention studies

Using data from a study conducted in Kenya, Ezzati and Kammen (2002) estimated that various energy- or behaviour-based interventions can result in a 35–95% reduction in exposure to PM_{10}. It is clear that acceptance of the intervention is a crucial component for its success and that, in each case, social, economic and environmental components need to be considered.

1.3.6 *Exposure in developed countries*

The previous sections have dealt with exposure from solid fuel combustion in developing countries; this section provides comparable figures on exposure from solid fuel combustion in developed countries. The two main sources of exposure to particles from biomass burning are wildfires and residential wood burning.

[Exposures due to agricultural burning also exist in developed countries but are localized in both space and time and do not affect a significant portion of the population. For example, in the early 1990s, agricultural burning in California contributed about 3.5 million tonnes per year to atmospheric particles, but that corresponded to only 1% of all emissions (Jenkins *et al.,* 1992). As an indication of the maximum PM concentrations that might be achieved, agricultural burning in Brazil is now carried out on a huge industrial scale, but is limited to 2 weeks per year; a 1-week monitoring programme during the burning season showed $PM_{3.5}$ levels of 191 μg/m^3, but this would correspond to a contribution to annual average concentrations of only 8 μg/m^3 (Reinhardt *et al*., 2001). Exposures elsewhere would in general be much smaller and therefore are not discussed further here.]

Wildfires are not dealt with here as they relate to outdoor exposure.

(a) Indoor air pollution

A study on a Navajo reservation in Arizona showed higher levels of respirable particles in homes that used wood for heating or cooking than in homes that used electricity or gas (Robin *et al*., 1996).

(b) Residential wood burning

All of the following studies relate to ambient (outdoor) air pollution due to wood burning for heating or to recreational use of fireplaces.

Source apportionment studies indicate that wood smoke is a major source of ambient PM during the winter months in several parts of the USA and Canada, particularly the western areas (Table 1.27). For example, 42% of the PM_{10} during winter months in San Jose, CA, was attributed to wood burning (Fairley, 1990). Chemical mass balance receptor-modelling of fine particles in Fresno and Bakersfield (CA) during wintertime identified both hardwood and softwood as sources of PM and organic compounds (Schauer & Cass, 2000), which were probably due to residential wood burning.

Outdoor PM levels in Seattle (WA) are also heavily influenced by residential woodstoves. Data from 3 years of sampling in Seattle were analysed for sources using positive matrix factorization (Maykut *et al*., 2003). The analysis found that vegetative burning contributed 34% to the total sources of PM in Seattle over 3 years.

Table 1.27. Wood smoke in developed countries: a sample of studies

Location	Wood smoke concentration	Reference
Indoor/personal		
Seattle personal	35% of total $PM_{2.5}$ mass	Larson *et al.* (2004)
Seattle indoor	49% of total $PM_{2.5}$ mass	Larson *et al.* (2004)
Fort Defiance, AZ	Indoor PM_{10} dominated by woodstove smoke	Robin *et al.* (1996)
Outdoor		
Santa Clara Co., CA	42% of chemical mass balance	Fairley (1990)
Seattle	62% of total $PM_{2.5}$ mass	Larson *et al.* (2004)
Atascadero, CA	Levoglucosan	Manchester-Neesvig *et al.* (2003)
Atlanta	11% of total $PM_{2.5}$ mass	Polissar *et al.* (2001)
Vermont	10–18% of $PM_{2.5}$	Polissar *et al.* (2001)
Christchurch, New Zealand	90% of $PM_{2.5}$ in winter	McGowan *et al.* (2002)

PM, particulate matter

Another study used a large data set from a 2-year exposure assessment and health effects panel study in Seattle during September 2000–May 2001. Data on indoor, outdoor, personal and fixed-site PM monitoring were available (Larson *et al.*, 2004). Five sources contributed to indoor and outdoor samples: vegetative burning, mobile emissions, secondary sulfate, a chlorine source and a crustal-derived source. Vegetative burning contributed the largest fraction of PM mass in all the samples (49%, 62% and 35% in indoor, outdoor and personal mass, respectively).

The distribution of particle-phase organic compounds was measured in communities that had children who participated in the Southern California Children's Health Study (Manchester-Neesvig *et al.*, 2003). Concentrations of levoglucosan, an efficient tracer for wood smoke aerosol, were seen in all 12 communities in the study. The average concentration increased in the winter, as would be expected for wood smoke emissions. The concentrations of levoglucosan were highest at the Atascadero site, which is about 15 miles inland. Earlier, these investigators identified two additional sugar anhydride tracers of wood smoke (galactosan and mannosan) in a study of urban sites in the San Joaquin Valley, CA (Nolte *et al.*, 2001).

In Canada, where the winters are cold and the forests are abundant, wood smoke is a major source of particle emissions.

Christchurch, New Zealand, is another city that is impacted by wood smoke. It is estimated that more than 90% of wintertime ambient PM comes from heating stoves and open fires burning wood (McGowan *et al.*, 2002). Frequent periods of air stagnation compound the problem by trapping PM near the ground and local meteorologists estimate that the relatively even mixing results in fairly homogeneous population exposure to PM.

Emissions inventories in Launceston, Australia, indicated that household wood burning accounted for 85% of annual PM_{10} emissions in 2000 (Jordan & Seen, 2005).

Source apportionment studies in Denmark showed that household wood burning was responsible for 47% of national $PM_{2.5}$ emissions in 2002 (Naeher *et al.*, 2007). In addition, household wood burning increased by about 50% during the 1990s, compared with only a 7% increase for total energy use.

Earlier studies of the contribution of wood smoke to ambient PM were summarized by Larson and Koenig (1994). Eighteen studies in 40 locations in the Pacific Northwest (Alaska, Washington, Oregon, Idaho, Montana) were included. The ranges of concentrations for $PM_{2.5}$ and PM_{10} were 12–68 $\mu g/m^3$ and 7–205 $\mu g/m^3$, respectively. The interquartile range for the fractional contributions of wood smoke to these concentrations was about 20–70% with a median value of 54%.

1.4 Interventions and policies to reduce exposure

(a) Encouragement of the adoption of efficient biomass stoves

One major solution that could provide a bridge between biomass energy and the switch to commercial fuels but is unfortunately overlooked is the improvement of stoves that burn biomass. This is generally less expensive for households that are dependent on biomass and these stoves are often designed with chimneys to vent smoke out of the home. It is generally accepted that improved biomass stoves reduce smoke in households that use them, but the reduction is not as significant as that for households that switch completely to LPG.

International programmes for improved stoves can provide some insights into both the successes and problems that are involved in the promotion of efficient biomass stoves (Sinton *et al.*, 2004a,c; Barnes *et al.*, 2007). In addition, energy efficiency and increasingly improved health are recognized to be important selling points for improved stoves.

During the last 30–40 years, diverse programmes have been initiated on household energy, from small-scale initiatives led by non-governmental organizations and communities to very ambitious national programmes, the largest of which has seen the installation of some 200 million improved stoves in rural China. Although few have been subjected to rigorous evaluation, the Indian national programme of improved cookstoves (Table 1.28), the Chinese national improved stoves programme (Table 1.29) (Smith *et al.*, 1993; Sinton *et al.*, 2004a) and the promotion of LPG (UNDP, 2004) have been assessed. Several smaller initiatives have also been reported: for example, the ceramic and metal stoves in East Africa which have proved popular and provided local employment (Njenga, 2001) and improved stove interventions in Guatemala (UNDP/ESMAP, 2003). Current projects also include the evaluation of several household energy programmes in India, Mexico and Guatemala, which seek to promote effective and sustainable markets for improved biomass stoves.

Table 1.28. Key features and lessons from the Indian national stove programme

The Indian National Programme of Improved Cookstoves was established in 1983 with goals common to many initiatives such as:

- conserving fuel,
- reducing smoke emissions in the cooking area and improving health conditions,
- reducing deforestation,
- limiting the drudgery of women and children and reducing cooking time, and
- improving employment opportunities for the rural poor.

While the Ministry of Non-Conventional Energy Sources was responsible for planning, setting targets and approving stove designs, state-level agencies relayed this information to local government agencies or non-governmental organizations. A Technical Backup Unit in each state trained rural women or unemployed youths to become self-employed workers to construct and install the stoves.

Between 1983 and 2000, the Programme distributed more than 33 million improved *chulhas*, but despite extensive government promotion efforts, improved *chulhas* now account for less than 7% of all stoves. Among those that have been adopted, poor quality and lack of maintenance have resulted in a lifespan of 2 years at most and typically much less. Evaluation of the Programme identified four main problems:

- Most states placed inadequate emphasis on commercialization, now seen as crucial for effective and sustainable uptake.
- Overall, there was insufficient interaction with users, self-employed workers and non-governmental organizations, so that designs did not meet the needs of households, and there was very poor uptake of user training.
- Quality control for installation and maintenance of the stove and its appropriate use was lacking.
- High levels of subsidy (about 50% of the stove cost) were found to reduce household motivation to use and maintain the stove.

The more successfully managed areas of the Programme focused resources on technical assistance, research and development, marketing and dissemination of information. Recently, the government of India decentralized the programme and transferred all responsibility for implementation to the state level. Since 2000, the Programme promotes only durable cement stoves with chimneys that have a minimum lifespan of 5 years. The introduction of these stoves will make adhesion to technical specifications and quality control much easier.

Table 1.29. Household impacts of China's National Improved Stove Programme

In 2002, an independent multidisciplinary evaluation was undertaken by a team of US and Chinese researchers to evaluate (i) implementation methods used to promote improved stoves, (ii) commercial stove production and marketing organizations that were created, and (iii) household impacts of the programmes, including health, stove performance, socioeconomic factors and monitoring of indoor air quality. The first two objectives were assessed through a facility survey of 108 institutions at all levels. The third objective was assessed through a survey of nearly 4000 households in three provinces: Zheijang, Hubei and Shaanxi. Key findings were:

- The household survey revealed highly diverse fuel usage patterns: 28 and 34 different fuel combinations were used in kitchens in winter and summer, respectively. Most households owned at least one or more coal and one or more biomass stoves; 77% of the biomass stoves but only 38% of the coal stoves were classified as improved. On average, improved stoves had a mean efficiency of 14%, which is well below the Programme target of between 20% and 30%, but above the mean efficiency of 9% for traditional stoves.

Table 1.29. (contd)

- With respect to air quality (measured by PM_4, the 'thoracic fraction' of particulate matter and carbon dioxide, coal stoves showed significantly higher concentrations than biomass stoves during the summer but not during the winter. Among households that used biomass fuels (but not among those that used combinations of fuels that included coal or LPG), improved stoves showed significantly lower PM_4 and carbon dioxide concentrations than traditional stoves.
- In both children and adults, coal use was associated with higher levels of exposure as measured by carbon dioxide in exhaled breath, and improved biomass stoves had lower levels. Reported childhood asthma and adult respiratory disease were negatively associated with use of improved stoves and good stove maintenance. These results should, however, be treated as indicative due to the limited sample size.

Overall, several important conclusions emerge with relevance to future improved stove programmes:

- A wide range of combinations of different fuel and stove types may limit the impact of an improved stoves programme.
- Given the importance of space heating, providing an improved biomass stove for cooking may not be a sufficient strategy to reduce indoor air pollution. There is a need to promote improved coal stoves among rural Chinese households.
- Even among households that used improved stoves, PM_4 and carbon dioxide levels were higher than Chinese national indoor air standards, implying that a large fraction of China's rural population is still chronically exposed to pollution levels substantially above those determined by the Chinese government to harm human health.

Implementation of the Chinese national programme differed substantially from that in India, and offers an interesting comparison. Although the rural populations concerned are poor, they have greater effective purchasing power than those in many developing countries, which allowed the development of a programme in which the majority of consumers purchased the stoves at almost full price (Smith *et al.*, 1993). Among the key features of the Chinese programme that are reported to have contributed to its success are decentralization of administration, a commercialization strategy that provided subsidies for the development of rural energy enterprises and quality control through the central production of critical components, such as parts of the combustion chamber, and engaging local technical institutions to modify national stove designs to meet local needs. National-level stove competitions generated contests among counties for contracts, to ensure local interest and allow the best-placed counties to proceed first; financial payments were only provided to counties after completion of an independent review of their achievements. No large flow of funds came from central government (in contrast, for example, with India, Table 1.30) and the major financial contributions were provided by local governments. As a result, delays and other problems associated with transferring large amounts of money were avoided. The Chinese programme succeeded in shifting norms: most biomass stoves now available on the market have flues and other technical features that classify them as improved.

Table 1.30. Characteristics of the national programme on improved *chulhas* in India compared with international experience

International practices in stove dissemination	Practices of the national programme on improved *chulhas*
Focus on need-based users	Targeted approach, stress on number of villages to be covered rather than households; demand for stoves not taken into consideration
Minimal subsidy for the stove from government or donors	Subsidy on stove accounted for the largest share (50%) of government support. Users in periurban areas were willing to pay greater amounts subject to guarantee on stove quality.
Maximum support for research and development, production and distribution of stoves, credit, capacity building and public awareness	Programme funded technical back-up units, but inadequate support given for research and development, with no such support extended to non-governmental organizations. Support for capacity and awareness generation not adequate
Close interaction among the designers, producers and users of stoves	Adequate interaction between producer and user, but interaction negligible between designer, and producer and user
Dependence on centralized production of stove and stove parts to enable availability to larger number of people due to lower cost of supply	For fixed stoves, there was no scope for centralized production as these are built at user's homes. Mass production of stove parts (chimney, cowl) undertaken by private manufacturer. No mass production of the firebox.
Onus on producers and designers to meet needs of consumers	Consumer needs met by self-employed workers/non-governmental organizations through changes in stove design with low inputs from designers.
Long-term funding	Long-term target-based funding by government routed through nodal agencies and disbursed through non-governmental organizations for implementation.

The lessons from international programmes have been compared with a programme in India that was recently cancelled due to poor performance. The most successful international programmes target subsidies for the commercialization of the stoves rather than providing the user with extensive subsidies. The idea is to stimulate entrepreneurs to build the stoves and to create a real market for them. The role of subsidies in India's programme is mixed. In the successful programmes, subsidies have encouraged possible stove owners to purchase them. However, once purchased, there are no follow-up subsidies for spare parts or maintenance. Subsidies can be used to support the development of the technical back-up units, quality control facilities for testing stoves, monitoring surveys to discern stove functionality and the opinions of users on the stoves, and training or education regarding subjects such as stove design, indoor air pollution and energy efficiency. However, this should be done in a way that integrates the design, construction and convenience of the stoves for users.

The best international programmes have developed stove programmes in the regions that have the greatest needs to conserve energy, such as those that have significant biomass shortages and emerging markets in the sale of fuelwood. The lack of availability of components and component parts appears to be a weakness in most of the programmes. Both producers and users complained about their availability and quality.

(b) Importance of electrification and other fuels

Electrification has an important role in development (International Energy Agency, 2002). There is some evidence from South Africa that communities with grid access experience lower pollutant exposure (Röllin *et al.*, 2004). Electricity is not expected to bring about large reductions in exposure to indoor air pollution in most low-income countries, however, since most poor households can only afford to use it for lighting and entertainment appliances but not for the much more energy-intensive and polluting requirements of cooking and space heating. The International Energy Agency (2002) has recently carried out a detailed review of electrification, including the issues involved in supply and cost recovery among poor (and especially rural) communities.

Experience in the promotion of LPG has also been reported, for example from the Indian Deepam Scheme (UNDP/ESMAP, 2002; World Bank, 2004b), and from the LPG rural energy challenge (UNDP, 2004). This latter initiative, developed by UNDP and the World LPG Association in 2002, promotes the development of new, viable markets for LPG in developing countries. Key elements include the development of partnerships in countries, enabling regulatory environments which facilitate LPG business development and product delivery, taking steps that reduce barriers to adoption: for example, the introduction of smaller (more affordable) gas bottles, and greater government and consumer awareness of costs and benefits. McDade (2004) has recently identified several key lessons that emerged from experience with the promotion of LPG markets.

(c) Key lessons

Too often, intervention technologies have been developed without adequate reference to users' needs, and as a result have been poorly used and maintained, or abandoned. Consequently, it is important to involve users, particularly women, in assessing needs and developing suitable interventions. Sustainable uptake should also be promoted through greater availability of a choice of appropriately priced interventions in local markets.

A wide variety of interventions are already available, and new technologies and approaches are emerging. However, the greatest challenge is in securing widespread uptake of effective interventions among those most at risk (in effect, the rural and urban poor), in ways that are sustainable. Enabling policy across sectors, and at different levels in societies, is required.

Although levels of indoor air pollution associated with biomass and other solid fuel use can be reduced substantially, particularly by stoves with flues, experience shows that exposure levels are not reduced as much due to the fact that emissions remain high and people are exposed in the vicinity of their homes and from neighbours' homes. Biomass stoves using secondary combustion may offer advantages due to much reduced emissions.

Cleaner fuels, in particular LPG and natural gas, offer the largest reductions in indoor air pollution and exposure, but cost and practical issues—in particular whether these fuels meet the needs of poor households—may result in lesser reductions being achieved in practice. Electricity is important for development, but is unlikely to contribute to substantial reductions in exposure to indoor air pollution as it is rarely used for cooking (and space heating where needed) in poor communities due to the high cost of supply infrastructure and use. Finally, behavioural changes can complement technical interventions, but appear to have limited potential alone.

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