BENEFITS AND COSTS OF HOUSEHOLD COOKING OPTIONS FOR AIR POLLUTION CONTROL

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Benefits and costs of addressing indoor air pollution challenges in Bangladesh

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Bangladesh Priorities

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Acronyms

AF	Attributable fraction
ALRI	Acute lower respiratory infection
CB	Chronic bronchitis
CBV	Cerebrovascular disease
CCC	Copenhagen Consensus Center
CI	Confidence Interval
COPD	Chronic obstructive pulmonary disease
CP	Cardiopulmonary disease
DALY	Disability adjusted life year
GBD	Global burden of disease
GDP	Gross domestic product
GS	Gasifier stove
HAP	Household air pollution
ICS	Improved cookstove
IHD	Ischemic heart disease
LC	Lung cancer
LPG	Liquefied petroleum gas
$\mu g/m^3$	microgram per cubic meter
OR	Odds ratio
PM	Particulate matter
PPP	Purchasing power parity
RR	Relative risk
SD	Standard deviation
VSL	Value of statistical life
YLD	Year lost to disease
YLL	Year of life lost to premature death
WHO	World Health Organization

Executive Summary

An estimated 3.9 million people died globally in 2010 from harmful exposure to PM2.5 emissions from cooking with solid fuels. This makes household air pollution (HAP) one of the leading health risk factors in developing countries. As many as 41% of households globally relied mainly on solid fuels for cooking in 2010. The prevalence of solid fuel use is especially high in Sub-Saharan Africa and in several countries in South and South-East Asia, including Bangladesh.

As many as 86-88% of households in Bangladesh cook with solid fuels, predominantly fuelwood but also agricultural residues and dung. The majority cooks in a separate building while over 20% cook outdoors and 12-20% cook in the house. Almost all households using solid fuels cook over open fire or an open stove.

PM2.5 personal exposures are in the hundreds of microgram per cubic meter from these cooking practices. This paper estimates that nearly 150,000 die in Bangladesh each year from this exposure, equivalent to about 15% of deaths from all causes.

The paper provides an assessment of benefits and costs of adopting cleaner cookstoves in Bangladesh. Three interventions are assessed: i) improved biomass cookstoves (ICS); ii) biomass gasifier stoves (GS); and iii) LPG stoves. Benefits assessed are health improvements, biomass fuel savings, and cooking time savings. Costs assessed are stove purchase, stove maintenance, LPG fuel purchase, and costs of stove promotion programs.

Improved biomass cookstoves provide benefits that are 3.6-7.7 times their cost. But health benefits of cooking with gasifier stoves or LPG are 3 times larger than cooking with an improved biomass cookstove. However these stove solutions are much more costly. Nevertheless, gasifier stoves provide benefit-cost ratios that are in the range of 2.8-7.2, or nearly as high as for improved cookstoves. Benefit-cost ratios for LPG are found to be much lower at 0.8-1.7 due to the cost of LPG fuel.

An estimated 33,000 deaths may be avoided each year if all households were to adopt ICS and 91,000 if all households adopt GS or LPG.

Benefit-cost ratios of interventions depend very much on pre-intervention PM2.5 personal exposure levels, and the magnitude of PM2.5 reductions achieved by the interventions. This is influenced by multiple factors, such as characteristics of dwellings, cooking location, cooking practices, and activity

patterns of household members. These factors can be positively modified by stove promotion programs to enhance the benefits of cleaner cookstoves.

Post-intervention PM2.5 exposure levels are also influenced by the condition of improved cookstoves. Promotion programs need therefore demonstrate and encourage proper use, maintenance and repairs of stoves.

The use of solid biomass cooking fuels by one household affects surrounding households. Smoke is vented out of one household for so to enter the dwellings of others and also pollute the ambient outdoor air. There are therefore benefits from stove promotion programs being community focused with the aim of achieving “unimproved stove free” and eventually “solid biomass free” communities along the lines of community lead sanitation programs and open defecation free communities.

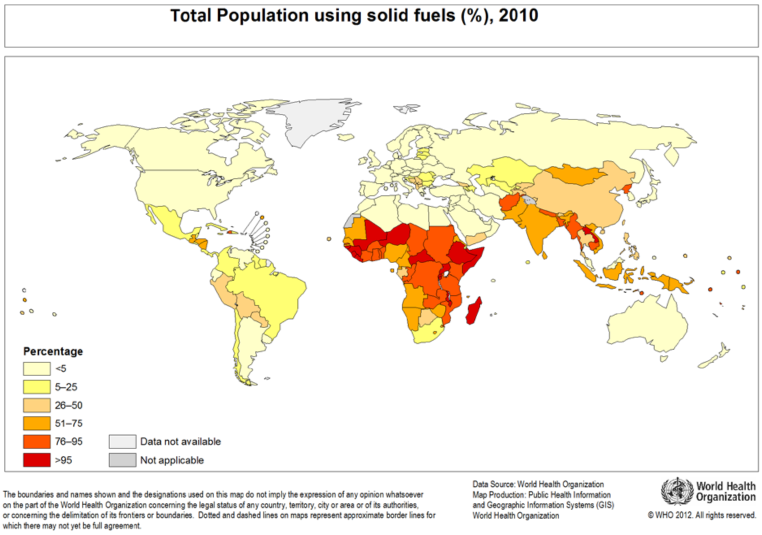
Large-scale adoption of cleaner cookstoves has had limited success in Bangladesh so far. Some of the factors influencing adoption rates are:

i) High initial cost of GS and LPG stove;
ii) High fuel cost for LPG;
iii) Need tailoring to consumers’ preferences for stove characteristics;
iv) Need installment financing;
v) Need well-targeted information campaigns;
vi) Need community focus (similar to total sanitation and “open defecation free” community programs.

Household use of solid biomass fuels

An estimated 3.9 million people died in 2010 from harmful exposure to PM2.5 emissions from cooking with solid fuels (Smith et al, 2014). This makes household air pollution (HAP) one of the leading health risk factors in developing countries (Lim et al, 2012). As many as 41% of households globally relied mainly on solid fuels for cooking in 2010 (Bonjour et al, 2013). The prevalence of solid fuel use is especially high in Sub-Saharan Africa and in several countries in South and South-East Asia, including Bangladesh (figure 1.1).

Figure 1.1 Prevalence of solid fuel use, 2010



Source: Presented in Smith et al (2014).

About 86-88% of the population of Bangladesh used solid fuels as their primary cooking fuel according to two national household surveys in 2011-2013 (table 1.1, figure 1.2). The most common solid fuel was wood, followed by crop residues/straw/shrubs/grass and dung.

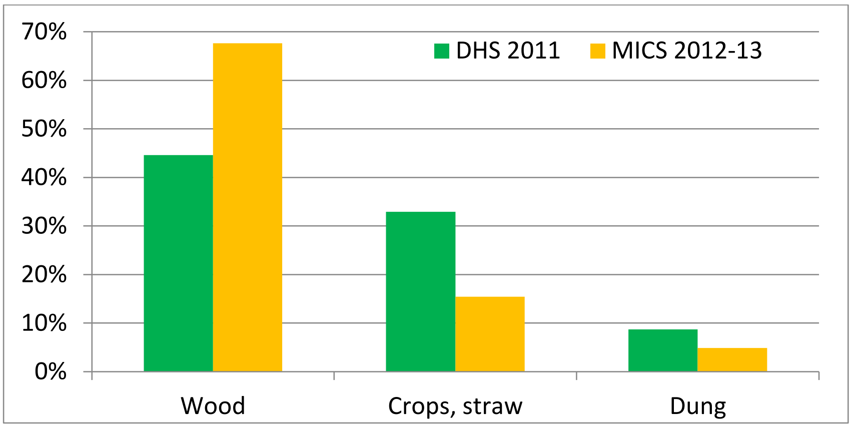
The most common modern fuel was natural gas (9%), followed by small amounts of LPG (< 1%). These fuels were predominantly used by the richest quintile of households and to some extent by the second richest quintile (BBS/UNICEF, 2014).

Table 1.1 Household primary cooking fuel in Bangladesh, 2011-2013 (% of population)

	DHS 2011	**MICS 2012-13**
Charcoal	0.2%	0.2%
Wood	44.6%	67.6%
Crops/straw/shrubs/grass	32.9%	15.4%
Dung	8.7%	4.9%
Total	**86.4%**	**88.1%**

Source: NIPORT et al (2013); BBS/UNICEF (2015).

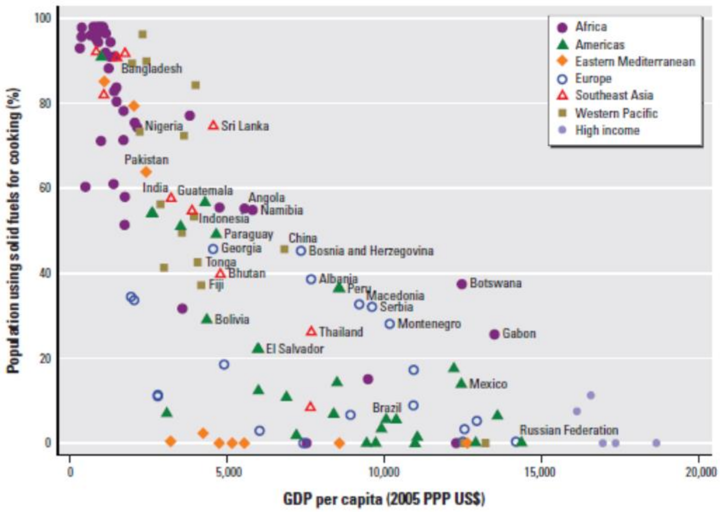
Figure 1.2 Household primary cooking fuel in Bangladesh, 2011-2013 (% of population)



Source: Produced from NIPORT et al (2013); BBS/UNICEF (2015).

The high prevalence of solid fuels for cooking in Bangladesh is to some extent explained by the country's relatively low GDP per capita. However, prevalence rates in countries at similar income level as Bangladesh vary from less than 40% to over 90%, suggesting that switching to modern, less polluting fuels can be achieved even at low income levels (figure 1.3).

Figure 1.3 Prevalence of solid fuel use in relation to GDP per capita



Source: Bonjour et al (2013).

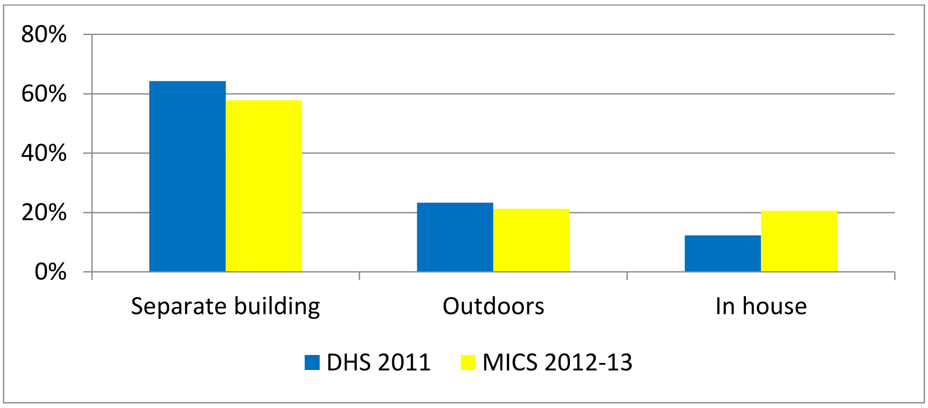
The majority of households cook in a separate building, and over 1/5th cook outdoors. In the range of 12-20% of households cook in the main house of which the vast majority cooks in a separate kitchen (table 1.2, figure 1.4). There are, however, large variations in place of cooking across the seven administrative divisions of Bangladesh. Cooking in a separate building ranges from 43% in Chittagong to 83% in Khulna. Outdoor cooking ranges from 7% in Khulna to 44% in Rajshahi. Cooking in the main house ranges from less than 3% in Rajshahi to 45% in Sylhet (BBS/UNICEF, 2015).

Table 1.2 Household place of cooking in Bangladesh, 2011-2013 (% of population)

	DHS 2011	MICS 2012-13
In the house (kitchen)	12.3%	16.7%
In the house (elsewhere)		3.9%
Separate building	64.3%	57.8%
Outdoors	23.3%	21.2%
Other	0.1%	0.3%
Total	**100%**	**100%**

Source: NIPORT et al (2013); BBS/UNICEF (2015).

Figure 1.4 Household place of cooking in Bangladesh, 2011-2013 (% of population)



Source: Produced from NIPORT et al (2013); BBS/UNICEF (2015).

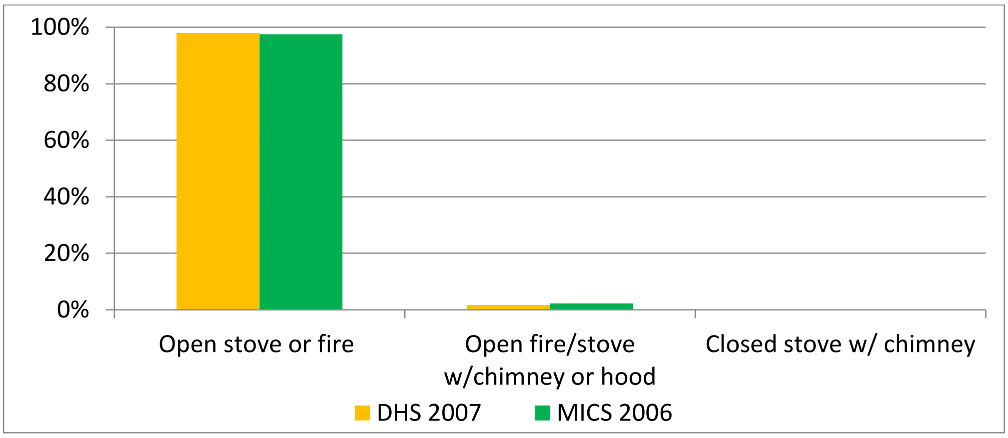
Nearly 98% of households using solid fuels cooked over open stove or fire with no chimney or hood in 2006-2007 (table 1.3). About 2% cooked over open stove or fire with chimney or hood, while almost no households had closed stoves with chimney. Type of stove was very similar across all divisions in Bangladesh expect for in Sylhet in which 22% of households cooked over open stove or fire with a chimney or hood. Nationally, the use of chimney or hood ranged from 1.1% among the poorest quintile of households to 5.1% among the richest quintile (BBS/UNICEF, 2007).

Table 1.3 Type of cookstoves among households using solid fuel in Bangladesh, 2006-2007

	DHS 2007	MICS 2006
Closed stove w/ chimney	0.0%	0.1%
Open fire/stove w/chimney or hood	1.7%	2.3%
Open stove or fire w/ no chimney or hood	97.9%	97.5%
Other	0.4%	0.0%
Total	**100%**	**100%**

Source: NIPORT et al (2009); BBS/UNICEF (2007).

Figure 1.5 Type of cookstoves among households using solid fuel in Bangladesh, 2006-2007



Source: Produced from NIPORT et al (2009); BBS/UNICEF (2007).

Household exposure to PM2.5

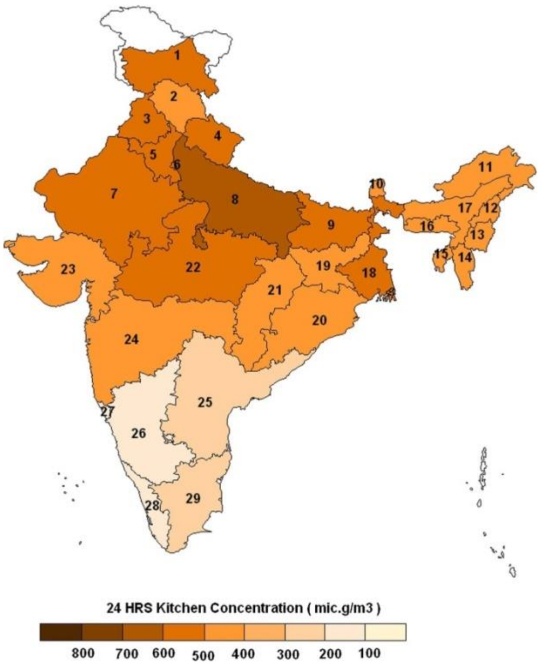
Air concentrations of PM2.5 from the use of solid biomass cooking fuels over open fire or in a traditional, unimproved stove often reach several hundred micrograms per cubic meter (μg/m^3) in the kitchen, and well over one hundred micrograms in the living and sleeping environments (WHO, 2014). Balakrishnan et al (2013) report PM.2.5 kitchen concentrations (24 hours) in several countries, generally in the range of 200-300 μg/m^3 to 1,100-1,300 μg/m^3.

PM2.5 concentrations vary substantially in relation to type of solid fuel, cooking location, type of stove and ventilation practices, cooking duration, and structure of dwelling. And household members' personal exposure to PM from combustion of solid fuels depends additionally on their activity patterns inside and outside the household environment.

Measurements of PM2.5 in the household environment in Bangladesh are relatively scarce, with no nationally representative studies or estimates. However, measurements from India can give a reasonable indication of concentration levels in Bangladesh. In households using solid cooking fuels in four states in India, PM2.5 concentrations (24 hours) averaged over 160 μg/m^3 in the living area and over 600 μg/m^3 in the kitchen. Type of fuel and kitchen, ventilation, geographical location and duration of cooking were found to be significant predictors of PM2.5 concentrations (Balakrishnan et al, 2013). These predictors were used by the authors to model 24-hours PM2.5 concentrations in kitchens and living areas in all states of India. Kitchen concentrations in the Indian states around Bangladesh are in the range of 421-501 μg/m^3 (figure 2.1).

Personal PM2.5 exposure is high as a result of these high indoor concentrations. Balakrishnan et al (2012) thus estimate a nationwide long-term PM2.5 personal exposure in households using solid fuels in India of 337 μg/m^3 among women, 285 μg/m^3 among children, and 204 μg/m^3 among men. These exposure estimates were applied in the GBD 2010 Project (Smith et al, 2014).

Figure 2.1 PM2.5 concentration in Indian kitchens (24 hr averages)



Source: Balakrishnan et al (2013).

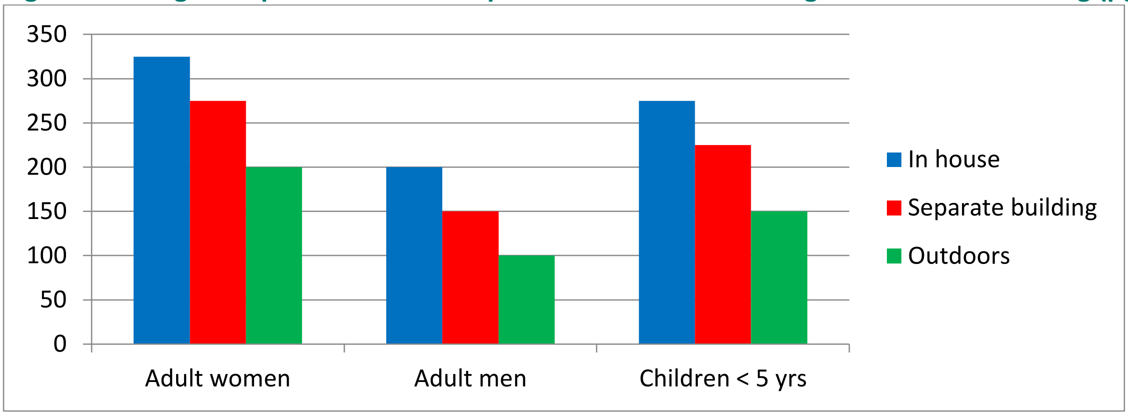
The personal exposure estimates reported above are applied as a baseline to households cooking *in the house* with solid fuels over open fire or traditional cookstove in Bangladesh. Exposure levels in households cooking in a separate building are somewhat lower, and lowest among households cooking outdoors (table 2.1; figure 2.2). These exposure levels reflect that a portion of biomass smoke from outdoor cooking or cooking in a separate building enters the indoor living and sleeping areas.

Table 2.1 Long term personal PM2.5 exposure in households using solid fuels for cooking (μg/m3)

	PM2.5 exposure by cooking location		
	In house	Separate building	Outdoors
Adult women	325	275	200
Adult men	200	150	100
Children < 5 years	275	225	150

Source: Estimates by the author.

Figure 2.2 Long term personal PM2.5 exposure in households using solid fuels for cooking (µg/m3)



Source: Estimates by the author.

Pollution control interventions

Benefits and costs of three household cooking interventions for household air pollution (HAP) control among households cooking with biomass fuels over open fire or traditional, unimproved cookstove are assessed in this paper:

(1) Improved biomass cookstove (ICS);
(2) Biomass gasifier stove (GS); and
(3) LPG stove (LPG).

Two-burner stoves are assessed, in contrast to single-burner stoves, so that households are less likely to continue to use their traditional stove for their cooking needs. The ICS assessed is a fixed Chulha stove with two-burners/pots and chimney. The Chulha stove is one of the dominant ICS in Bangladesh (Accenture, 2012; Winrock, 2012). Biomass gasifier stoves turn biomass at very high temperatures into clean burning gas. These stoves are being promoted in Asia and Africa (World Bank, 2015a; 2014). The LPG stove also has two burners.

Pre- and post-intervention assessment is undertaken with respect to:

(1) Household member PM2.5 exposure reduction;
(2) Health benefits of reduced PM2.5 exposure;
(3) Non-health benefits (i.e., fuel savings and cooking time savings);
(4) Stove and fuel costs of interventions; and
(5) Comparison of benefits and costs of each intervention (i.e., benefit-cost ratios).

The interventions are also assessed for two targeting scenarios:

(1) Random (high community pollution (CP)); and

(2) Community focused (some community pollution (SCP).

Household use of solid fuels has community effects. Smoke from fuel burning enters dwellings of other households as well as contributes to outdoor ambient air pollution. An improved stove with chimney, or simply venting of smoke through a hood from any stove or open fire, may be effective for the household installing these devices, but contributes to increased outdoor ambient pollution and indoor pollution in nearby dwellings. Only "smokeless" fuels and technologies prevent this problem of externalities.

To achieve the maximum benefits per unit of expenditure on household energy and stove interventions, all households would need to participate, and thus achieve a "solid fuel use free" community or, alternatively, an "unimproved stove free" community. This concept may be applicable to rural areas where communities are spatially separated from another, and is similar to an "open defecation free" community in the sanitation sector, often promoted and achieved through community-lead or total sanitation campaigns.

Post-intervention PM2.5 exposures

Scenarios of pre- and post-intervention levels of personal exposure to PM2.5 are presented in table 4.1 and figure 4.1. These exposure levels are broad averages and will vary substantially across individual households.

Improved biomass cookstoves (ICS) reduce 24-hour and long term exposures to 75-150 $\mu g/m^3$. Exposure reductions are largest in households cooking in the house and for adult women who are generally responsible for cooking in Bangladeshi households. Exposure reductions from this intervention is least pronounced, yet still substantial, for households cooking outdoors and for adult males who generally spend the least time in and around the household environment.

Bottled LPG is by far the most common modern energy used for cooking in developing countries. Combustion of LPG results in very little PM emissions and is therefore considered a relatively clean cooking fuel. Studies have however found that household PM2.5 concentrations often remain as high as 40-60 $\mu g/m^3$, presumably mainly due to the community effects of neighboring households using solid fuels.

The scenario in this study therefore stipulates that exposure levels associated with cooking with gasifier stoves (GS) or LPG converge to 50 $\mu g/m^3$. This is independent of cooking location as these cooking options do not cause significant PM2.5 emissions. The main sources of PM2.5 exposure in these households are other sources of PM2.5 in their own household environment and community pollution (e.g., other households using solid fuels). As the entire community converts to GS or LPG, personal exposure levels converge to 25 μg/m^3, with PM2.5 pollution remaining from other sources in their own household environment and non-solid fuel related outdoor ambient PM2.5.

Personal exposure levels in households using GS or LPG may even decline to level below 25 μg/m^3. Joon et al (2011) found a 24-hour average PM2.5 exposure for the cook of 25 μg/m^3 among rural households using LPG in Haryana, India. Titcombe and Simcik (2011) measured an average PM2.5 personal exposure of 14 μg/m^3 in households in the southern highlands of Tanzania cooking indoors with LPG.

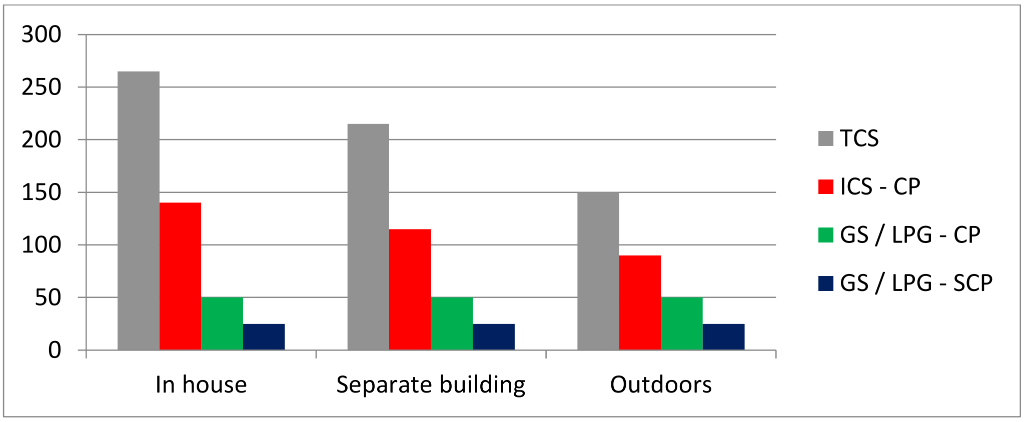
Thus the exposure levels in table 4.1 represent households living in a community in which other households to a varying extent continue to use biomass fuels in unimproved and/or improved cookstoves or in which air quality is affected by other sources of PM2.5 pollution, i.e., affected by community pollution or pollution originating outside the community.

Table 4.1. Household air pollution exposure levels by intervention level and exposure group

	Adult females			Adult males			Children < 5		
	In house	Separate building	Outdoors	In house	Separate building	Outdoors	In house	Separate building	Outdoors
TCS	325	275	200	200	150	100	275	225	150
ICS - CP	150	125	100	125	100	75	150	125	100
GS / LPG - CP	50	50	50	50	50	50	50	50	50
GS / LPG - SCP	25	25	25	25	25	25	25	25	25

Note: TCS = Traditional cookstove (biomass over open fire or unimproved stove); ICS = Improved Cook Stove; GS = Gasifier stove; LPG = Liquified Petroleum Gas stove; CP = Community pollution; SCP = Some community pollution.
Source: The author.

Figure 4.1. Average household air pollution exposure levels



Note: Averages for adult women, adult men, and young children.
Source: The author.

Health benefits of interventions

The GBD 2010 Project assessed five major health outcomes from long term exposure to PM2.5 in the household environment: (i) ischemic heart disease (IHD), (ii) cerebrovascular disease (stroke), (iii) lung cancer, and (iv) chronic obstructive pulmonary disease (COPD) among adults females and males, and (v) acute lower respiratory infections (ALRI) among children under five years of age (Lim et al 2012).

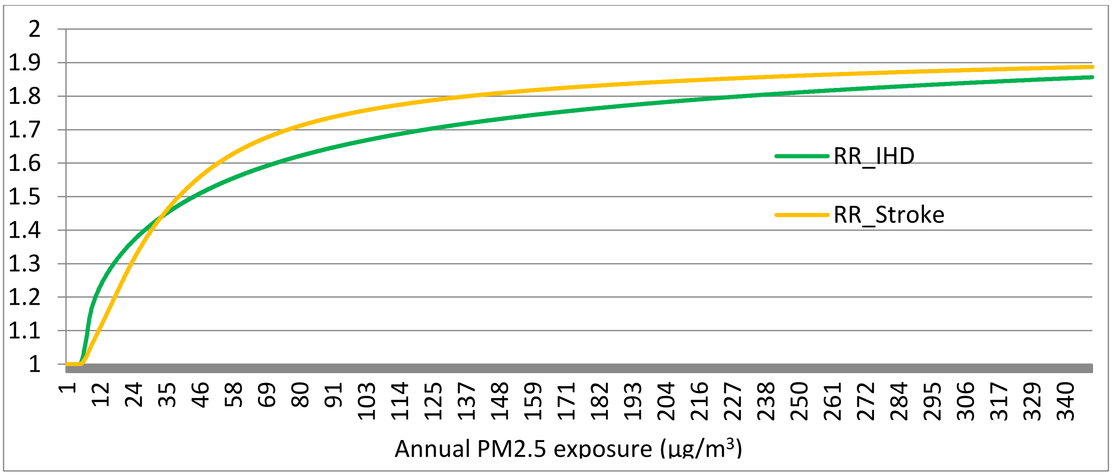
Health benefits of moving from pre-intervention to post-intervention exposure levels can be estimated by using the integrated PM2.5 exposure-health response methodology from the GBD 2010 Project presented in annex 1 and risk ratios presented in Apte et al (2015) and Smith et al (2014).

An estimated 80% of premature mortality from household air pollution (HAP) exposure in Bangladesh is IHD and stroke. The relative risk and PM2.5 exposure relationships for these two health outcomes are highly non-linear (figure 5.1). Thus the health benefits of reducing exposure from 200-300 μg/m^3 to 100 μg/m^3 are relatively minor.

This is evident in table 5.1. Improved cook stoves (ICS) yield "only" 11-15% reduction in health effects if community pollution remains high and 19-24% reduction if all households adopt ICS. In contrast, gasifier stoves and LPG yield almost three times larger reduction in health effects, but still with over 1/3rd of health effects remaining if PM2.5 exposure is not reduced to levels below 25 μg/m^3.

Overall, this paper estimates that nearly 150,000 people currently die in Bangladesh each year from this exposure, equivalent to about 15% of deaths from all causes. About 33,000 deaths may be avoided each year if all households were to adopt ICS and 91,000 if all households adopt GS or LPG.

Figure 5.1 Relative risk of ischemic heart disease (IHD) and stroke mortality from long term PM2.5 exposure



Note: Age-weighted relative risks. Source: Produced from Apte et al (2015).

Table 5.1 Reduction in health effects of household air pollution in Bangladesh

	Improved cook stove	Gasifier stove	LPG
Random adoption (high community pollution)	11-15%	32-41%	32-41%
Community adoption (some / low community pollution)	19-24%	55-65%	55-65%

Source: Estimates by the author.

Non-health benefits of interventions

Switching to an improved cookstove (ICS) or to a gasifier stove (GS) or LPG also has non-health benefits. Main benefits are reduced biomass consumption, whether self-collected or purchased, and reduced cooking time. The magnitude of these benefits will depend on current cooking arrangements, type of improved stove, household cooking patterns, and household member valuation of time savings.

Fuel savings

Common energy conversion efficiencies for unimproved stoves, or cooking over open fire, are in the range of 13-18% for wood and 9-12% for agricultural resides and dung. Reported efficiencies of improved biomass cookstoves are 23-40% for wood and 15-19% for agricultural residues (Malla and Timilsina, 2014). This means that efficiency gains from using an improved stove instead of an unimproved stove or open fire generally exceed 25% and can be more than 100% depending on type of stoves, cooking practices and type of food cooked. Consequently, biomass fuel savings therefore generally exceed 20% and can be nearly 70% using wood.

In this paper it is assumed that average biomass fuel savings are 40% from the use of an improved cookstove and 50% from the use of a gasifier stove (Servals, 2012), instead of an unimproved stove or open fire. Use of LPG results in 100% savings of biomass fuels.

Many urban households purchase some or all of the biomass fuels they use for cooking while the majority of rural households collects these fuels themselves. It is important to impute a value of these self-collected fuels. A common approach is to impute a value based on the amount of time households spend on biomass fuel collection.

A collection time of 30 minutes per household per day among households using unimproved biomass stoves or open fire, a female rural wages rate of BDT 25 per hour, and a value of time equal to 50% of the female wage rate is applied for valuation of household fuel collection. A female wage rate is applied as most fuel collection is carried out by women (or children). The estimated value of biomass fuel savings are presented in table 6.1.[1]

Table 6.1 Estimated value of household fuel savings, 2014

	Bangladesh
Biomass fuel collection time (minutes/household/day)	30
Female rural wage rate (Taka/hour)	25
Value of time (% of wage rate)	50%
Value of biomass fuel collection (Taka/household/year)	2,270
Value of biomass fuel savings (Taka/household/year)	
Improved cookstove (40% savings)	908
Gasifier stove (50% savings)	1,135
LPG stove (100% savings)	2,270

Source: Author's estimates.

Cooking time savings

Households in developing countries typically spend 3-5 hours per day on cooking. Hutton et al (2006) report that it takes 11-14% less time to boil water with a Rocket stove (improved cookstove) or LPG stove than over open fire. Habermehl (2007) reports that monitoring studies have found that cooking time declined by 1.8 hours per day with the use of a Rocket Lorena stove. One-quarter of this time, or 27 minutes, is considered time savings by Habermehl, as the person cooking often engages in multiple household activities simultaneously. Siddiqui et al (2009) report that daily fuel burning time for cooking in a semi-rural community outside Karachi was 30 minutes less in households using natural gas than in households using wood, and that time spent in the kitchen was 40 minutes less. Jeuland and Pattanayak (2012) assumes that an improved wood stove saves around 10 minutes per day and that LPG saves one hour per day in cooking time.

Garcia-Frapolli et al (2010) report that cooking time from using the improved Patsari chimney stove in Mexico declined by about 1 hour per household per day. Effectively 15-30 minutes of this time is saved as the person cooking often engages in multiple household activities simultaneously.

This paper applies a cooking time saving of 15 minutes per day from the use of an improved cookstove and 40 minutes from the use of a gasifier stove or LPG compared to an unimproved cookstove or open fire. The cooking time saving for a gasifier stove is adjusted downwards by 15 minutes per day (Servals, 2012) from 40 to 25 minutes to account for increased fuel preparation time, i.e., chopping of wood into pieces suitable for the gasifier stove. As for fuel collection time savings, a value of time equal to

[1] This is likely a somewhat underestimate of the value of biomass fuels used by households as households also purchase some of their fuels at a higher price than reflected in the valuation of collection time.

50% of female rural wage rates are applied to estimate the value of cooking time savings. Annual value of time savings per household are presented in table 6.2.

Table 6.2. Estimated value of cooking time savings, 2012

	Taka/household/year
Improved biomass cookstove	1,135
Gasifier stove*	1,892
LPG stove	3,027

* Net of increased fuel preparation time. Source: Author's estimates.

Costs of interventions

Cost of stoves

Cost of improved biomass cookstoves varies tremendously depending on fuel and emission efficiency, durability, materials, and technology. Basic improved stoves can cost less than US$10 but these stoves often do not provide fuel savings beyond 25%, provide limited emission reduction benefits, and have poor durability. Intermediate improved stoves cost US$25-35 and include Rocket stoves. These stoves can provide up to 50% fuel savings and substantial emission reduction benefits. Advanced stoves such as natural or forced draft gasifier stoves cost US$50-75 but often have only one burner. The price of an LPG stove with a single burner can cost less than US$ 40.

Stove costs and useful life of the stoves applied in this paper are presented in table 7.1. The cost is for stoves that have two burners or, alternatively, for two single stoves so that cooking with the traditional, unimproved stove or open fire can be avoided.

The improved cookstove is a Chulha stove with two burners/pots and chimney. The version made of concrete is reported to cost up to BDT 1,800 (Accenture, 2012; Winrock, 2012). Biomass gasifier stoves come in various models, technologies and prices (World Bank, 2015a; 2014). . The one assessed here is a high-end version costing BDT 5,000 per single burner stove. LPG stoves with multiple burners are reported to cost up to BDT 11,000 (Accenture, 2012).

Cost of LPG fuel

It is here assumed that LPG consumption is 30 kg per person per year for households that exclusively use LPG for cooking. This is in line with estimates for several countries in Asia, Africa and South America (Kojima et al, 2011). The economic price of LPG is assumed to be BDT 80 per kg (table 7.1).

Table 7.1. Estimates of stove and fuel costs

	Improved Biomass Cookstove	Gasifier Stove	LPG Stove and Fuel
Cost of stove (Taka)	1,600	10,000	8,000
Useful life of stove (years)	3	6	10
LPG fuel (kg/person/year)			30
LPG fuel (kg/household/year)			140
LPG cost (Taka/kg)			80
LPG fuel cost (Taka/household/year)			11,200

Source: The author.

Cost of stove maintenance and stove promotion programs

Cost of interventions also includes stove maintenance and repairs of improved cookstoves and LPG stoves. Annual cost of maintenance and repair is assumed to be 5% of initial stove cost.

Achieving adoption of modern energy and improved stoves for cooking requires promotion, community participation, and behavioral change programs. Such programs cost money and is part of the cost of achieving targets. Program cost increases on the margin as increased intensity and scale of programs are needed to achieve an increasing share of the population switching to modern energy or improved stoves.

Programs are assumed to cost BDT 800 per household in the first year (promotion and monitoring), and BDT 100 per household per year in subsequent years (monitoring).[2]

[2] Garcia-Frapolli et al (2010) apply a similar cost for maintenance and repair of a Patsari stove in the Purepecha region of Mexico, and a program cost of US$ 25 per stove.

Benefit-cost ratios

Valuation of health benefits

Household air pollution control is unlikely to instantaneously provide full benefits for health outcomes that develop over long periods of PM2.5 exposure, i.e., for heart disease, stroke, chronic obstructive pulmonary disease (COPD) and lung cancer. It is therefore assumed that reduced incidence of and deaths from these diseases are gradually realized over ten years. For acute lower respiratory infections (ALRI) among young children, however, full health benefits are realized in the same year as PM2.5 exposure reduction. This means that over a time horizon of 20 years annualized health benefits are 71-79% of full benefits, i.e., of the estimated health benefits presented in section 5.[3]

Avoided deaths and associated illness from cleaner cookstoves can be monetized by using various benefit valuation measures. The Copenhagen Consensus Center (CCC) has suggested to apply a value of GDP per capita per avoided "disability adjusted life year" or DALY.

An common alternative approach that attempts to reflect how much people are willing to pay to reduce the risk of death is the use of the so-called value of statistical life (VSL) for valuation of avoided deaths.

A VSL of BDT 4.8 million (US$ 61,672) is estimated for Bangladesh for the year 2014 in this paper (annex 2), equivalent to 50 times GDP per capita. Along with valuation of a day of illness at 50% of wage rates in Bangladesh, this approach results in estimated health benefits that are 2.2 times larger than when using GDP per capita for a DALY. Health benefits using both approaches are presented in this paper.

Benefits and costs

Benefits and costs of interventions are compared by using their ratio. Thus a benefit-cost ratio (BCR) greater than one indicates that benefits exceed costs. The ratio can be calculated as the present value of benefits over the present value of costs, or as annualized benefits over annualized costs. Discount rates of 3%, 5% and 10% are used in the calculations.

BCRs of improved biomass cookstoves (ICS), biomass gasifier stoves (GS) and LPG stoves are presented in table 8.1 for two health benefit valuation scenarios. Valuation of health benefits using VSL is

[3] Discount rate is 3 to 10%.

denoted as “high” and GDP per capita for a DALY as “low”. Benefits of cooking time and fuel savings are the same in each scenario.

The BCRs are averages for the three cooking locations prevalent in Bangladesh. As seen in Annex 3 the BCRs do not differ substantially across cooking locations, albeit pre- and post-intervention levels of PM2.5 are higher for cooking in the house than cooking in separate building, and higher for cooking in separate building than cooking outdoors. The reason for the similarity of BCRs is mainly that the incremental health benefits per μg/m^3 reduction in PM2.5 exposure is smaller at higher initial exposure levels associated with the shape of the integrated exposure response (IER) function described in Annex 1.

BCRs for partial and full community adoption of interventions are presented separately. Significant community pollution continues to prevail with partial adoption, thus BCRs are lower than for full community adoption. The BCRs for full adoption are 25-45% higher than for partial adoption.

The BCRs for ICS and GS are quite similar. They are in the range of 3.6-7.7 for ICS and 2.8-7.2 for GS. However, absolute benefits of GS are 2-3 times higher than the benefits of ICS, mainly due to the substantially higher health benefits.

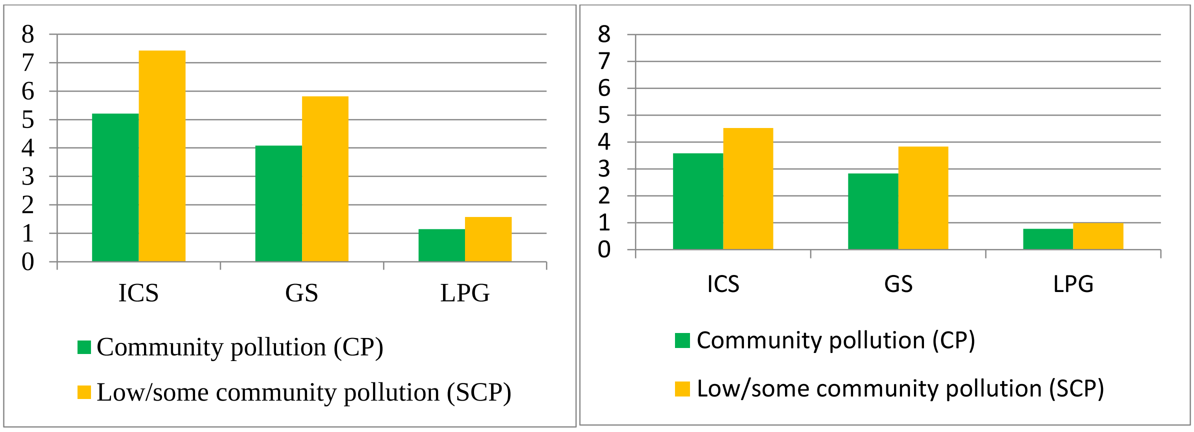
BCRs for LPG are in the range of 0.8-1.7, indicating that costs are about as large as benefits. This is because of the substantial fuel costs, albeit health benefits are as high as for the gasifier stove.

Table 8.1 Benefit-cost ratios of interventions, 2014

	“High”		“Low”	
	Partial adoption	Full adoption	Partial adoption	Full adoption
	Community pollution (CP)	Low/some community pollution (SCP)	Community pollution (CP)	Low/some community pollution (SCP)
ICS	5.6	7.7	3.6	4.5
GS	5.0	7.2	2.8	3.8
LPG	1.2	1.7	0.8	1.0

Note: The BCRs in this table reflect a discount rate of 5%. BCRs with a range of discount rates are presented in Annex 3.
Source: Estimates by the author.

Figure 8.1 Benefit-cost ratios of partial (CP) vs community wide adoption (SCP) of cleaner cookstoves



Note: Left and right chart reflect "high" and "low" health benefit valuation scenario, respectively. The BCRs in this table reflect a discount rate of 5%. BCRs with a range of discount rates are presented in Annex 3.
Source: Estimates by the author.

While benefit-cost ratios of improved cookstoves may be higher than for gasifier stoves, and substantially higher than for LPG, clean energy is the only option for effectively combatting health effects of solid fuels, especially when achieved community-wide. In other words, improved cookstoves may be the efficient but not a very effective solution.

Summary and conclusions

As many as 86-88% of households in Bangladesh cook with solid fuels, predominantly fuelwood but also agricultural residues and dung. The majority cooks in a separate building while over 20% cook outdoors and 12-20% cook in the house. Almost all households using solid fuels cook over open fire or an open stove.

PM2.5 personal exposures are in the hundreds of microgram per cubic meter from these cooking practices, with severe health effects in the form of disease and premature mortality.

Improved biomass cookstoves provide benefits that are 3.6-7.7 times their cost. But health benefits of cooking with gasifier stoves or LPG are 3 times larger than cooking with an improved biomass cookstove. However these stove solutions are much more costly. Nevertheless, gasifier stoves provide benefit-cost ratios that are in the range of 2.8-7.2, or nearly as high as for improved cookstoves. Benefit-cost ratios for LPG are found to be much lower at 0.8-1.7 due to the cost of LPG fuel.

Benefit-cost ratios of interventions depend very much on pre-intervention PM2.5 personal exposure levels, and the magnitude of PM2.5 reductions achieved by the interventions. This is influenced by multiple factors, such as characteristics of dwellings, cooking location, cooking practices, and activity patterns of household members. These factors can be positively modified by stove promotion programs to enhance the benefits of cleaner cookstoves.

Post-intervention PM2.5 exposure levels are also influenced by the condition of improved cookstoves. Promotion programs need therefore demonstrate and encourage proper use, maintenance and repairs of stoves.

The use of solid biomass cooking fuels by one household affects surrounding households. Smoke is vented out of one household for so to enter the dwellings of others and also pollute the ambient outdoor air. There are therefore benefits from stove promotion programs being community focused with the aim of achieving "unimproved stove free" and eventually "solid biomass free" communities along the lines of community lead sanitation programs and open defecation free communities.

Large-scale adoption of cleaner cookstoves has had limited success in Bangladesh so far. Some of the factors influencing adoption rates are:

vii) High initial cost of GS and LPG stove;
viii) High fuel cost for LPG;
ix) Need tailoring to consumers' preferences for stove characteristics;
x) Need installment financing;
xi) Need well-targeted information campaigns;
xii) Need community focus (similar to total sanitation and "open defecation free" community programs.

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Annex 1. Health effects of particulate matter pollution

Health effects of PM exposure include both premature mortality and morbidity. The methodologies to estimate these health effects have evolved as the body of research evidence has increased.

Outdoor particulate matter air pollution

Over a decade ago, Pope et al (2002) found elevated risk of cardiopulmonary (CP) and lung cancer (LC) mortality from long term exposure to outdoor PM2.5 in a study of a large population of adults 30 or more years of age in the United States. CP mortality includes mortality from respiratory infections, cardiovascular disease, and chronic respiratory disease. The World Health Organization used the study by Pope et al when estimating global mortality from outdoor air pollution (WHO 2004; 2009). Since then, recent research suggests that the *marginal increase* in relative risk of mortality from PM2.5 declines with increasing concentrations of PM2.5 (Pope et al 2009; 2011). Pope et al (2009; 2011) derive a shape of the PM2.5 exposure-response curve based on studies of mortality from active cigarette smoking, second-hand cigarette smoking (SHS), and outdoor ambient PM2.5 air pollution.

Household particulate matter air pollution

Combustion of solid fuels for cooking (and in some regions, heating) is a major source of household air pollution (HAP) in most developing countries. Concentrations of PM2.5 often reach several hundred micrograms per cubic meter ($\mu g/m^3$) in the kitchen and living and sleeping environments. Combustion of these fuels is therefore associated with an increased risk of several health outcomes, such as acute lower respiratory infections (ALRI) in children, chronic obstructive pulmonary disease (COPD) and chronic bronchitis (CB), and lung cancer in adults. The global evidence is summarized in meta-analyses by Desai et al (2004), Smith et al (2004), Dherani et al (2008), Po et al (2011), and Kurmi et al (2010). Risks of health outcomes reported in these meta-analyses are generally point estimates of relative risks of disease (with confidence intervals) from the use of fuel wood, coal and other biomass fuels[4] relative to the risks from use of liquid fuels (e.g., LPG).

A randomized intervention trial in Guatemala found that cooking with wood using an improved chimney stove, which greatly reduced PM2.5 exposure, was associated with lower systolic blood pressure (SBP) among adult women compared to SBP among women cooking with wood on open fire (McCracken et al, 2007). Baumgartner et al (2011) found that an increase in PM2.5 personal exposure was associated with an increase in SBP among a group of women in rural households using biomass

[4] Other biomass fuels used for cooking is mostly straw/shrubs/grass, agricultural crop residues and animal dung.

fuels in China. These studies provide some evidence that PM air pollution in the household environment from combustion of solid fuels contributes to cardiovascular disease.

An integrated exposure-response function

The Global Burden of Disease 2010 Study (GBD 2010 Study) takes Pope et al (2009; 2011) some steps further by deriving an integrated exposure-response (IER) relative risk function (RR) for disease outcome, *k*, in age-group, *l,* associated with exposure to fine particulate matter pollution ($PM_{2.5}$) both in the outdoor and household environments:

$$RR(x)_{kl} = 1 \qquad \text{for } x < x_{cf} \qquad \text{(A1.1a)}$$

$$RR(x)_{kl} = 1 + \alpha_{kl}(1 - e^{-\beta_{kl}(x-x_{cf})^{\rho_{kl}}}) \qquad \text{for } x \geq x_{cf} \qquad \text{(A1.1b)}$$

where x is the ambient concentration of $PM_{2.5}$ in $\mu g/m^3$ and x_{cf} is a counterfactual concentration below which it is assumed that no association exists. The function allows prediction of RR over a very large range of $PM_{2.5}$ concentrations, with $RR(x_{cf}+1) \sim 1+\alpha\beta$ and $RR(\infty) = 1 + \alpha$ being the maximum risk (Shin et al, 2013; Burnett et al, 2014).

The parameter values of the risk function are derived based on studies of health outcomes associated with long term exposure to ambient particulate matter pollution, second hand tobacco smoking, household solid cooking fuels, and active tobacco smoking (Burnett et al, 2014). This provides a risk function that can be applied to a wide range of ambient $PM_{2.5}$ concentrations around the world as well as to high household air pollution levels of $PM_{2.5}$ from combustion of solid fuels.

The disease outcomes assessed in this paper, as in the GBD 2010 Study, are ischemic heart disease (IHD), cerebrovascular disease (stroke), lung cancer, chronic obstructive pulmonary disease (COPD), and acute lower respiratory infections (ALRI) (Lim et al 2012; Mehta et al 2013). The risk functions for IHD and cerebrovascular disease are age-specific with five-year age intervals from 25 years of age, while singular age-group risk functions are applied for lung cancer (≥ 25 years), COPD (≥ 25 years), and ALRI in children (< 5 years). An x_{cf} = 7.3 $\mu g/m^3$ is applied here based on bounds of 5.8 to 8.8 $\mu g/m^3$ used in the GBD 2010 Study (Lim et al, 2012).

The population attributable fraction of disease from PM2.5 exposure is then approximated by the following expression:

$$PAF = \sum_{i=1}^{n} P_i[RR\left(\frac{x_i+x_{i-1}}{2}\right) - 1]/(\sum_{i=1}^{n} P_i[RR(\frac{x_i+x_{i-1}}{2}) - 1] + 1) \qquad \text{(A1.2)}$$

where P_i is the share of the population exposed to PM2.5 concentrations in the range x_{i-1} to x_i. This attributable fraction is calculated for each disease outcome, *k*, and age group, *l*. The disease burden (B) in terms of annual cases of disease outcomes due to PM2.5 exposure is then estimated by:

$$B = \sum_{k=1}^{t} \sum_{l=1}^{s} D_{kl} AF_{kl} \quad \text{(A1.3)}$$

where D_{kl} is the total annual number of cases of disease, *k*, in age group, *l*, and AF_{kl} is the attributable fraction of these cases of disease, *k*, in age group, *l*, due to PM2.5 exposure.

The potential impact fraction is applied to estimate the reduction in disease burden from a change in the population exposure distribution that can result from an intervention to control PM2.5 exposure levels among a sub-set of the population:

$$PIF = [\sum_{i=1}^{n} P_i RR\left(\frac{x_i + x_{i-1}}{2}\right) - \sum_{i=1}^{n} P_i' RR\left(\frac{x_i + x_{i-1}}{2}\right)]/(\sum_{i=1}^{n} P_i RR(\frac{x_i + x_{i-1}}{2}) \quad \text{(A1.4)}$$

where P'_i is the population exposure distribution after the intervention. The reduction in annual cases of disease outcomes is then estimated by:

$$\Delta B = \sum_{k=1}^{t} \sum_{l=1}^{s} D_{kl} PIF_{kl} \quad \text{(A1.5)}$$

This approach is applied to IHD, stroke and ALRI using the RRs from the IER function reported by Apte et al (2015).

Relative risks for COPD and lung cancer follow the approach in Smith et al (2014). This was also applied in the GBD 2010 Project. RRs are larger for COPD and smaller for lung cancer than the RRs from the IER function reported by Apte et al (2015).

Annex 2. Valuation of health benefits

Two valuation measures are considered for estimating the benefit of avoided illness is in this paper: i) a day of disease is valued as 50% of average labor income per day; or ii) a year lost to disease (YLD) is valued at GDP per capita as suggested by the Copenhagen Consensus Center (CCC).

Two valuation measures are considered for estimating the benefit of an avoided death in this paper: i) the value of statistical life (VSL); or ii) a year of life lost (YLL) to premature mortality is valued at GDP per capita as suggested by CCC.

A VSL for Bangladesh is estimated based on Navrud and Lindhjem (2010). Navrud and Lindhjem conducted a meta-analysis of VSL studies for OECD based exclusively on stated preference studies which arguably are of greater relevance for valuation of mortality risk from environmental factors than hedonic wage studies. These stated preference studies are from a database of more than 1,000 VSL estimates from multiple studies in over 30 countries, including in developing countries. Navrud and Lindhjem provide an empirically estimated benefit-transfer (BT) function from these stated preference studies that can be applied to estimate VSL in any country or region. A modified BT function with income elasticity of one is applied here:[5]

$$\ln VSL = 0.22 + 1.0 \ln(gdp) - 0.445 \ln(r) \qquad \text{(A2.1)}$$

where *VSL* is expressed in purchasing power parity (PPP) adjusted dollars; *gdp* is GDP per capita in PPP adjusted dollars; and *r* is the change in risk of mortality.[6] The VSL is then converted to a country's currency by multiplying by the PPP rate as reported in World Bank (2015b), which is the ratio "GDP in local currency / PPP adjusted GDP in dollars".

Applying the BT function also involves specifying change in mortality risk (r). The mortality risk from environmental factors depends on the environmental factor at hand. Most stated preference studies of VSL use a mortality risk in the range of 1/10,000 to 5/10,000 per year. A mid-point risk of 2.5/10,000 per year is applied in this paper.

The VSL estimated for Bangladesh for the year 2014 by this methodology is BDT 4.79 million, or about 50 times GDP per capita that year (table A2.1).

Table A2.1 Economic data and VSL for Bangladesh, 2014

GDP per capita	BDT 95,864	Bangladesh Bureau of Statistics
Average monthly wage	BDT 7,307	International Labour Organization
Value of statistical life (VSL)	BDT 4,787,591	Calculated from equation A2.1

[5] A later version of their paper (Lindhjem et al, 2011) reports income elasticities in the range of 0.77 – 0.88 for a screened sample of VSL studies.

[6] This BT function implies that the income elasticity is 1.0, meaning that VSL varies across countries in proportion to their PPP adjusted GDP per capita level.

Annex 3. Benefit-cost ratios

Benefit-cost ratios (BCR) are presented in tables A3.1a-c and A3.1a-c for cookstove interventions in three household cooking locations, using VSL for valuation of mortality (denoted as ”high”) and, alternatively, GDP per capita for valuation of a disability adjusted life year (DALY) (denoted as “low”). Benefits and costs are annualized values per household. Annualized benefits decline with higher discount rates, as the present value of future benefits fall. Annualized costs increase with higher discount rates, as much of the cost is up-front.

Table A3.1a. Benefits and costs of interventions with cooking in the house (BDT/household/year) (“high”)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	5,112	1,004	**5.1**	5,019	1,019	**4.9**	4,792	1,057	**4.5**
GS	14,660	2,536	**5.8**	14,307	2,626	**5.4**	13,449	2,854	**4.7**
LPG	16,930	12,422	**1.4**	16,578	12,505	**1.3**	15,719	12,722	**1.2**

Table A3.1b. Benefits and costs of interventions with cooking in a separate building (BDT/household/year) (“high”)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	6,219	1,004	**6.2**	6,092	1,019	**6.0**	5,784	1,057	**5.5**
GS	13,976	2,536	**5.5**	13,644	2,626	**5.2**	12,836	2,854	**4.5**
LPG	16,246	12,422	**1.3**	15,915	12,505	**1.3**	15,107	12,722	**1.2**

Table A3.1c. Benefits and costs of interventions with outdoor cooking (BDT/household/year) (“high”)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	5,178	1,004	**5.2**	5,083	1,019	**5.0**	4,852	1,057	**4.6**
GS	10,852	2,536	**4.3**	10,615	2,626	**4.0**	10,038	2,854	**3.5**
LPG	13,123	12,422	**1.1**	12,885	12,505	**1.0**	12,308	12,722	**1.0**

Table A3.2a. Benefits and costs of interventions with cooking in the house (BDT/household/year) (“low”)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	3,398	1,004	**3.4**	3,357	1,019	**3.3**	3,257	1,057	**3.1**
GS	8,162	2,536	**3.2**	8,006	2,626	**3.0**	7,627	2,854	**2.7**
LPG	10,432	12,422	**0.8**	10,276	12,505	**0.8**	9,898	12,722	**0.8**

Table A3.2b. Benefits and costs of interventions with cooking in a separate building (BDT/household/year) ("low")

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	3,886	1,004	**3.9**	3,831	1,019	**3.8**	3,695	1,057	**3.5**
GS	7,860	2,536	**3.1**	7,714	2,626	**2.9**	7,357	2,854	**2.6**
LPG	10,130	12,422	**0.8**	9,984	12,505	**0.8**	9,627	12,722	**0.8**

Table A3.2c. Benefits and costs of interventions with outdoor cooking (BDT/household/year) ("low")

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	3,427	1,004	**3.4**	3,385	1,019	**3.3**	3,283	1,057	**3.1**
GS	6,481	2,536	**2.6**	6,376	2,626	**2.4**	6,122	2,854	**2.1**
LPG	8,751	12,422	**0.7**	8,647	12,505	**0.7**	8,392	12,722	**0.7**

These BCRs presented above are for the situation in which the interventions are adopted by only a portion of households (i.e., partial adoption), thus significant community pollution continues to prevail. The average BCRs for the three cooking locations, with partial adoption are presented in tables A3.3a-b. This can be contrasted with 25-45% higher BCRs if full adoption is achieved (tables A3.4a-b), resulting in much lower community pollution and thus higher health benefits to all households.

Table A3.3a. Average benefits and costs of household cooking interventions (BDT/household/year) ("high" with partial adoption of interventions)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	5,801	1,004	**5.8**	5,688	1,019	**5.6**	5,410	1,057	**5.1**
GS	13,368	2,536	**5.3**	13,055	2,626	**5.0**	12,292	2,854	**4.3**
LPG	15,638	12,422	**1.3**	15,325	12,505	**1.2**	14,562	12,722	**1.1**

Table A3.4a. Average benefits and costs of household cooking interventions (BDT/household/year) ("high" with full adoption of interventions)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	8,048	1,004	**8.0**	7,866	1,019	**7.7**	7,423	1,057	**7.0**
GS	19,506	2,536	**7.7**	19,006	2,626	**7.2**	17,790	2,854	**6.2**
LPG	21,776	12,422	**1.8**	21,276	12,505	**1.7**	20,061	12,722	**1.6**

Table A3.3b. Average benefits and costs of household cooking interventions (BDT/household/year) ("low" with partial adoption of interventions)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	3,702	1,004	**3.7**	3,652	1,019	**3.6**	3,529	1,057	**3.3**
GS	7,592	2,536	**3.0**	7,453	2,626	**2.8**	7,117	2,854	**2.5**
LPG	9,862	12,422	**0.8**	9,724	12,505	**0.8**	9,387	12,722	**0.7**

Table A3.4b. Average benefits and costs of household cooking interventions (BDT/household/year) ("low" with full adoption of interventions)

	3% discount rate			5% discount rate			10% discount rate		
	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**	Benefit	Cost	**BCR**
ICS	4,694	1,004	**4.7**	4,613	1,019	**4.5**	4,418	1,057	**4.2**
GS	10,301	2,536	**4.1**	10,080	2,626	**3.8**	9,544	2,854	**3.3**
LPG	12,571	12,422	**1.0**	12,351	12,505	**1.0**	11,814	12,722	**0.9**

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